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NBS REPORT
6736

SECOND QUARTERLY REPORT

to

National Aeronautics and Space Administration

on

Cryogenic Research and Development

for

Quarter Ending December 31, 1960

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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
BOULDER LABORATORIES
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NATIONAL BUREAU OF STANDARDS REPORT

NBS PROJECT		NBS REPORT
81410, 81420, and 81430	December 31, 1960	6736

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1. Physical Properties of Fluid Hydrogen

1.1 Heat Capacity and PVT Measurements

Dr. R. D. Goodwin (Project Leader), D. E. Diller, H. M. Roder, Dr. L. A. Weber, Dr. B. A. Younglove

The PVT measurements on parahydrogen are being conducted by D. E. Diller and L. A. Weber with assistance from R. D. Goodwin and occasionally from H. M. Roder. H. M. Roder is programming and conducting the computations with the electronic machines and is also examining the data for self-consistency. The heat capacity calorimeter design details are being attacked by B. A. Younglove full-time and L. A. Weber part-time, and the methods required to obtain thermodynamic functions from experimental data have been surveyed by R. D. Goodwin.

Among the Appendices is a confirmation, by vapor-pressure observations, that we have indeed had parahydrogen in the pipet. PVT data in the range 28 through 70 cc/g. mol is presented (experimental runs Nos. 3 through 31). Experiments to much higher densities have been completed (through run No. 42). The highest densities, above the point of solidification near 200 atm., are about to be measured. Following that, the low-pressure measurements required for computation of thermodynamic functions will be undertaken in the range of amagat density from 300 to 30.

This portion of this report was originally prepared as part of a different report series. References to earlier reports in this other series occur in several places in the Appendices and should be ignored.

APPENDIX I

Thermodynamic Functions from PVT Data

1. Methods are discussed in general and in detail by authors of references [1-7] in that order. The change in thermodynamic functions with pressure or density at constant temperature may be computed from PVT data. The paths of such computations are vertical straight lines on figures 1 and 2, prepared for this discussion. It is necessary to choose some standard or reference state. This leads to confusion because in the natural reference state of zero pressure the functions A, S, and G have logarithmic infinites. The figures show that isothermal access to the liquid region from low densities is blocked by the coexistence region. The choice of density, rather than pressure, as an independent variable together with temperature yields more regularly-behaved functions for computational purposes. A separate task, therefore, is a final interpolation from density to pressure as independent variable for engineering applications. The selection of functions and procedures for computation is discussed below.

2. Reference or Standard States. Professor Michels takes a value of zero for energy and entropy, E and S, under standard conditions, 0°C at 1 atm. To obtain values for S along the reference line of amagat density $\rho = 1$ at different temperatures, the specific heat as a function of temperature at $\rho = 1$ is required [2]. H. W. Woolley on the other hand tabulates thermodynamic functions "for a fictitious ideal gas" at one atmosphere pressure as a function of temperature [4] from computations of spectroscopic data by statistical mechanical methods [7,8]. The situation of these reference or standard states, $\rho = 1$ and $P = 1$ atm., relative to the phases of hydrogen is shown by the figures mentioned.

3. Basic Functions. Residual functions are a difference between values for real and ideal gas at the same temperature and density. Whether explicitly stated [3] or not, they are used in actual computation [4]. A defined residual function of the data, Q*, simplifies computations utilizing density as an independent variable [3],

$$Q^* \equiv (Pv - RT)v = RT(Z - 1)v. \tag{1}$$

This function is related to isochores, showing the same regular behavior with temperature and density. Extrapolation of Q* isotherms to zero density gives RT·B where B is the second virial coefficient. All of the residual thermodynamic functions, equation (13-a), approach zero with density (no logarithmic infinities). From only two such functions the others may be obtained rather directly. With density as a variable, the residual Helmholtz free energy may be obtained without differentiation of the data,

$$A^*(u, T) = \int_0^u Q^* du_T, \tag{2}$$

where $u \equiv 1/v$ is density and data must be used to sufficiently low density for acceptable error in this residual.

Any additional thermodynamic function (variables u and T) now requires differentiation of the data. It is pointed out by F. Din [1], however, that it may be preferable with precise and closely-spaced data to perform differentiation after an operation such as equation (2). The alternatives are

$$S^*(u, T) = -\int_0^u (\partial Q^*/\partial T)_u du_T \tag{3-a}$$

and

$$S(u, T) = -(\partial A/\partial T)_u. \tag{3-b}$$

The remaining residual functions are

$$E^* = A^* + TS^* \tag{4}$$

$$H^* = E^* + Pv - RT \tag{5}$$

$$G^* = H^* - TS^* \tag{6}$$

$$\ln(f/P) = A^*/RT - \ln Z + Z - 1 \tag{7}$$

A check is given by application of

$$(\partial G/\partial P)_T = v \tag{8}$$

to results with pressure as independent variable.

4. Specific Heats. These are highly exacting of data accuracy and precision:

$$C_v = -T\int_o^u (\partial^2 Q^*/\partial T^2)_u du_T, \tag{9-a}$$

$$C_p^* - C_v^* = -R + T(\partial P/\partial T)_v^2/(\partial P/\partial v)_T. \tag{10-a}$$

As an alternative, however, the second differentiation may occur at a late stage of the computations,

$$C_v = (\partial E/\partial T)_v, \tag{9-b}$$

$$C_p = (\partial H/\partial T)_p. \tag{10-b}$$

5. Residuals from Equation of State. When graphical methods are employed, it is imperative for accuracy to handle only suitable residual quantities. At very high densities any real fluid shows such extreme deviation from ideal gas behavior that the conventional residuals [3] no longer are relatively small. It is necessary then to utilize an equation of state for reference rather than ideal gas [6]. We eschew this method since, for the extreme range of densities to be handled, it may be expected that the residuals from any possible equation of state would not be well-behaved. Computational labor,

moreover, becomes excessive. The close-spacing of our data, together with electronic computer-methods, may permit use of the conventional residuals.

6. Michels' Residuals. Take entropy and energy as zero at the standard state, 0°C and $P_o = 1$ atm., amagat density $\rho \equiv v_o^o/v = 1$. Entropy at any other temperature on the $\rho = 1$ isochore is

$$S_{(1,T)} \equiv S_{(1,T)} - S_{(1,273)} = \int_{273}^{T} (Cv)_{\rho=1} d\ln T. \tag{11}$$

Corresponding Helmholtz energy could be obtained with

$$(\partial A/\partial T)_v = -S. \tag{12}$$

Professor Michels prefers to determine E on this isochore via a path through $\rho = 0$, [2]. One then has $A \equiv E - TS$.

The residual A^* of any thermodynamic function A is defined by

$$A^*(u,T) \equiv \int_0^u [(\partial A/\partial u)_T - (\partial A/\partial u)_T^o]\, du_T, \tag{13-a}$$

where the superscript o indicates perfect gas. If relative values for A have been determined at all temperatures along the $\rho = 1$ isochore, values at other densities on an isotherm are given by

$$\Delta A \equiv A(\rho,T) - A(1,T) = \int_1^{\rho} (\partial A/\partial \rho)_T d\rho_T \tag{14-a}$$

$$\Delta A = \int_1^{\rho} (\partial A/\partial \rho)_T^o\, d\rho_T + \int_1^{\rho} [(\partial A/\partial \rho)_T - (\partial A/\partial \rho)_T^o]\, d\rho_T \tag{14-b}$$

$$\Delta A = \int_1^{\rho} (\partial A/\partial \rho)_T^o d\rho_T + A^*(\rho,T) - A^*(1,T). \tag{14-c}$$

If A be Helmholtz energy, then

$$(\partial A/\partial \rho)^{o}_{T} = -RT/\rho \tag{15}$$

and

$$A^*(\rho, T) = u^{o}_{o}\int_{o}^{\rho} Q^* d\rho_{T}, \tag{16}$$

where $u^{o}_{o} \equiv 1/v^{o}_{o}$ is density at standard state, 0°C, $P_{o} = 1$ atm., where molal volume is v^{o}_{o}. Equation (14-c) then becomes

$$\Delta A = -RT \ln \rho + u^{o}_{o}\left[\int_{o}^{\rho} Q^* d\rho_{T} - \int_{o}^{1} Q^* d\rho_{T}\right], \tag{17-a}$$

$$A(p, T) = A(1, T) - RT \ln \rho + u^{o}_{o}\int_{1}^{\rho} Q^* d\rho_{T}. \tag{17-b}$$

For entropy, the relations corresponding to (15) and (16) are

$$(\partial S/\partial \rho)^{o}_{T} = -R/\rho \tag{18}$$

and

$$S^*(\rho, T) = -u^{o}_{o}\int_{o}^{\rho} (\partial Q^*/\partial T)_{\rho} d\rho_{T} \tag{19}$$

wherewith equation (14-c) becomes

$$S(\rho, T) = S(1, T) - R \ln \rho - u^{o}_{o}\int_{1}^{\rho} (\partial Q^*/\partial T)_{\rho} d\rho_{T}. \tag{20}$$

7. Woolley's Procedure. This differs from Michels' procedure in two essentials: the reference states are on an isobar $P_{o} = 1$ atm.; these states are for hypothetical ideal gas, rather than real gas. The residual definition of equation (13-a) may be rewritten

$$A(u, T) \equiv A^{o}(u, T) + A^*(u, T), \tag{13-b}$$

where A^o is any thermodynamic function for perfect gas. To avoid the logarithmic infinities in the functions A^o, S^o and G^o for the perfect gas at zero pressure, the spectroscopically computed values $A^o(u_o, T)$ at $P_o = 1$ atm., corresponding to $u_o(T)$, are employed for reference at each T,

$$A^o(u,T) = A^o(u_o,T) + \int_{u_o}^{u} (\partial A/\partial u)^o_T du_T. \tag{21}$$

Equation (13-b) then becomes

$$A(u,T) = A^o(u_o,T) + \int_{u_o}^{u} (\partial A/\partial u)^o_T du_T + A^*(u,T), \tag{22-a}$$

or

$$A(\rho,T) = A^o(\rho_o,T) + \int_{\rho_o}^{\rho} (\partial A/\partial \rho)^o_T d\rho_T + A^*(\rho,T), \tag{22-b}$$

where ρ_o, the amagat density of perfect gas at $P_o = 1$ is temperature-dependent.

If A be Helmholtz energy, then by equation (15)

$$\int_{\rho_o}^{\rho} (\partial A/\partial \rho)^o_T d\rho_T = -RT \ln \rho + RT \ln \rho_o. \tag{23}$$

But we find the temperature-dependence of ρ_o as follows for perfect gas,

$$\rho_o \equiv v_o^o/v_o \text{ where } v_o = RT/P_o, \tag{24}$$

whence

$$\rho_o = (P_o v_o^o / RT_o)(T_o/T). \tag{25}$$

Combining equations (16), (23), and (25) with (22-b) for Helmholtz energy,

$$A(\rho, T) = A^{o}(\rho_{o}, T) - RT \ln \rho + RT \left[\ln (P_{o} v_{o}^{o} / RT_{o}) + \ln(T_{o}/T) \right]$$
$$+ u_{o}^{o} \int_{o}^{\rho} Q^{*} d\rho_{T}. \qquad (26)$$

The corresponding expression for entropy is derived by exact analogy,

$$S(\rho, T) = S^{o}(\rho_{o}, T) - R \ln \rho + R \left[\ln (\rho_{o} v_{o}^{o} / RT_{o}) + \ln (T_{o}/T) \right]$$
$$- u_{o}^{o} \int_{o}^{\rho} (\partial Q^{*} / \partial T)_{\rho} d\rho_{T}. \qquad (27)$$

The first terms on the right of equations (26) and (27) represent the tabulated reference values for hypothetical ideal gas at one atmosphere pressure.

8. Orthobaric Densities. Some curvature of isochores near saturation, not shown by figure 1, may be suspected. If experimental isochores were measured with very small temperature increments extending into the coexistence region, a set of isochores would define the vapor pressure curve. Such desirable measurements usually are not undertaken as a part of PVT work because of the greatly increased labor. If heats of vaporization and the vapor pressure curve (curvature) are known, the difference between orthobaric densities may be computed. Hence the density of saturated liquid, from triple to critical points, is valuable data. This could be utilized more directly with the rule of rectilinear diameter, provided two vapor densities were known [15]. Some such information is required to extrapolate ordinary PVT isochores onto the coexistence boundary.

9. Compressed Liquid Region. Entry to this region requires computation of functions of density along an isotherm which crosses the

coexistence region. Applicable relations for the crossing are

$$\Delta S \equiv Q/T, \tag{28}$$

$$(\partial S/\partial v)_T = (\partial P/\partial T)_v, \tag{29}$$

$$(\partial A/\partial v)_T = -P. \tag{30}$$

Upon integration of (29) and (30) in the coexistence region and elimination of Δv_T,

$$\Delta A_T = -Q/(\partial \ln P/\partial \ln T). \tag{31}$$

Thermodynamic properties in the compressed liquid region cannot be related to any low-pressure standard state by means of PVT data alone. Latent heats [10,11] and the vapor pressure curve [14] must be known. An alternative is to employ a specific heat measurement, C_v, extending from the triple point through the compressed liquid region to a temperature well above critical where the functions are determined by PVT data alone, figure 1,[7].

10. <u>Low Pressure Data Requirements.</u> While our interest and measurements are concerned with high density regions, we find that a self-consistent table of thermodynamic properties preferably is based upon some low-density standard or reference states: equations (26) and (27), for example. Just how low in density must experimental measurements be extended? Isothermal plots of Q* <u>vs.</u> ρ become linear at low density. The linear portions provide values for second and third virial coefficients. In principle these isotherms should cover the temperature range of the subsequent calculations. In practice some extrapolation of the virial coefficients to lower temperatures may be necessary. Figure 8 of the compendium of Woolley <u>etal.</u> [4] shows that the hydrogen plots are linear in the range $\rho \leqslant 200$. Our figure 2 shows that this covers most of the gas

and vapor region of densities less than critical ($\rho_c \approx 335$). Our apparatus is capable of measurements to densities as low as $\rho = 20$. We therefore should be able to determine second and third virial coefficients by means of data from $\rho = 20$ to $\rho = 200$, with resulting isothermal equations of state valid for $0 \leqslant \rho \leqslant 200$ excluding the condensed phases.

11. Discussion. A commendable procedure of Woolley etal. [4] is to maintain separate tabulations of terms in equations such as (26). Any errors in individual terms will not invalidate tables of the others. Our figures show that the $\rho = 1$ isochore does not penetrate the coexistence region. For simplicity of conception, therefore, the virial equation could be employed with equations (26) and (27), together with spectroscopic data for ideal parahydrogen, to compute a table of thermodynamic function values at integral temperatures along the $\rho = 1$ isochore. Equations (17-b) and (20) then would be applicable with the virial equation for isothermal computations as a function of increasing density, with upper limit the coexistence boundary or limit of validity of the virial equation at about $\rho = 200$.

12. Tentative Computational Tables. The following list of tables may serve as a guide to the computational tasks required:

1. Functions for ideal gas at 1 atm. and integral temperatures.
2. Functions for real gas at $\rho = 1$ and integral temperatures.
3. The change in fucntions between $\rho = 1$ and $\rho = \rho_i$, where the integral values of ρ_i extend to the coexistence boundary for integral temperatures up to critical, and to about $\rho = 200$ at higher

integral temperatures, employing the virial equation up to "third" coefficient, and direct PVT data for the vapor region $200 \leq \rho \leq \rho_c$.

4. The change in functions upon crossing the coexistence region, vapor to liquid, at integral temperatures up to critical.
5. The change in functions of compressed liquid from each state of saturation up to integral densities, ρ_i, extending to the solid or limit of PVT data, at integral temperatures up to critical.
6. The change in functions of gas and fluid from about $\rho = 200$ to integral values ρ_i extending to the limit of PVT data at integral temperatures above critical.

R. D. G.

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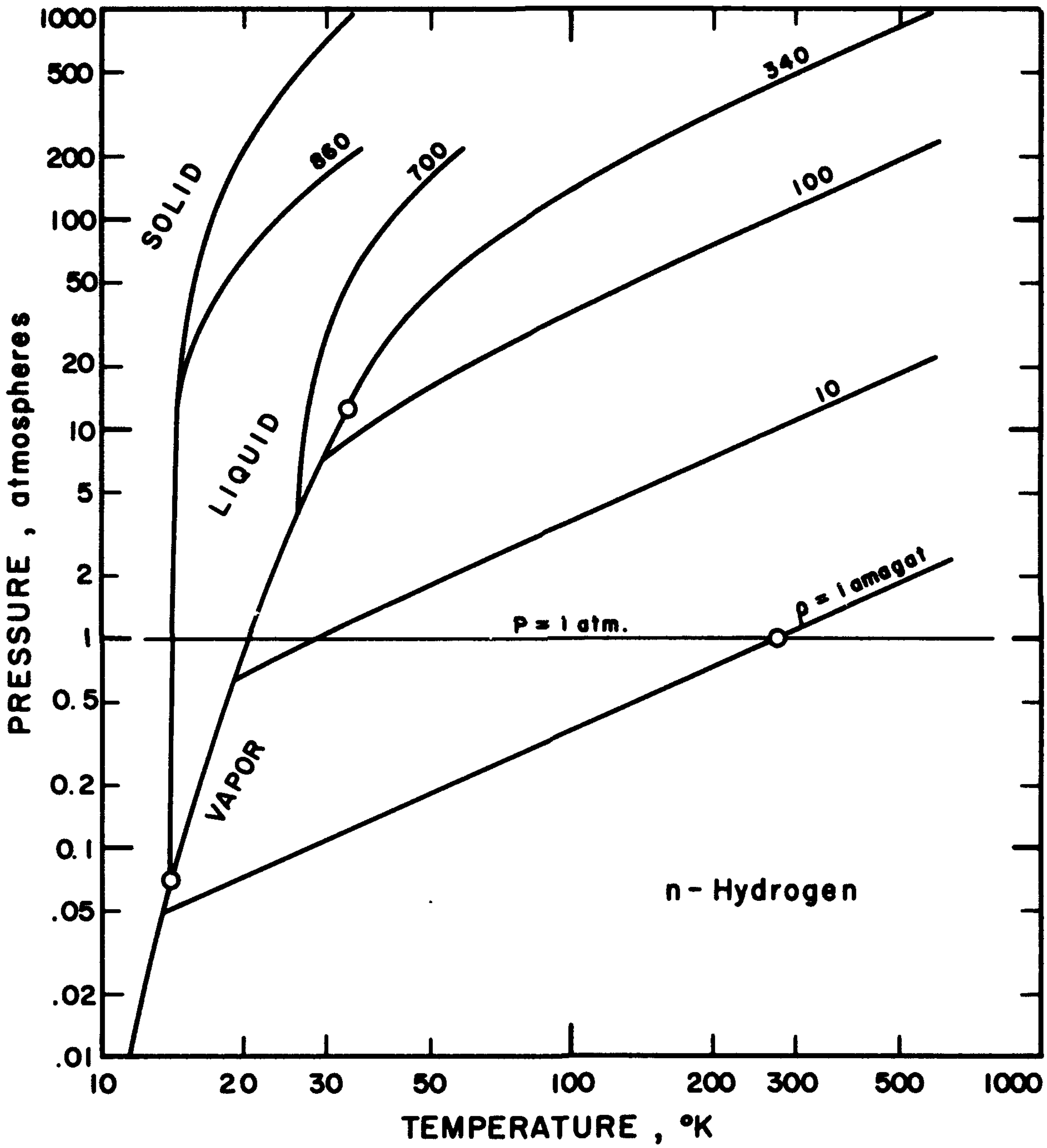
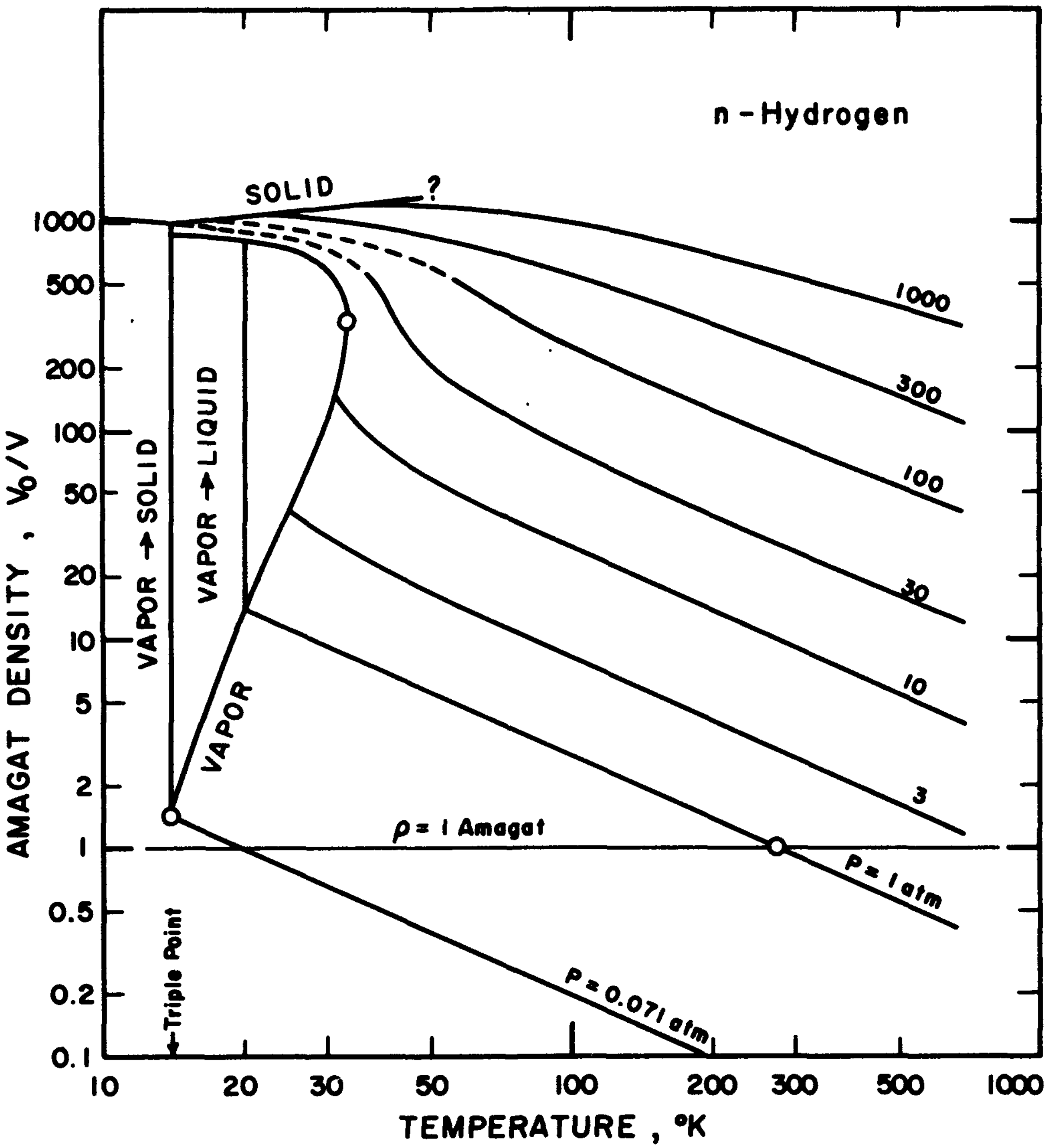

1000
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
.05
.02
.01
PRESSURE , atmospheres
10
20
30
50
100
200
300
500
1000
TEMPERATURE , °K
SOLID
LIQUID
VAPOR
860
700
340
100
10
P = 1 atm.
ρ = 1 amagat
n - Hydrogen

Figure 1·



n - Hydrogen
SOLID
?
1000
300
100
30
10
3
P = 1 atm
P = 0.071 atm
ρ = 1 Amagat
VAPOR → SOLID
VAPOR → LIQUID
VAPOR
Triple Point
AMAGAT DENSITY , V0/V
1000
500
200
100
50
20
10
5
2
1
0.5
0.2
0.1
10
20
30
50
100
200
300
500
1000
TEMPERATURE , °K

Figure 2

APPENDIX II

Expansion of Approximate Equation of State

In seeking regularly-behaved isotherms for examination of the precision of experimental densities, and therefore also comparison with the virial equation, it might be useful to expand the equation of state (Report 13, page 18) units of cc., g.mol., atm., degree Kelvin,

$$Pv/RT = v/(v - b + c/v) - (A/RTv^{m-1})\,[1 - (v_o/v)^n]. \qquad (1)$$

$$\begin{array}{ll} b = 26.9 & v_o = 23.478 \\ c = 237.5 & m = 1.86 \\ A = 125{,}000 & n = 6 \end{array}$$

The expansion of the first term of (1) converges for molal volumes greater than 7 cc.,

$$v/(v - b + c/v) = 1 + b_1u + c_1u^2 + d_1u^3 + e_1u^4 + f_1u^5 + \cdots, \qquad (2)$$

where the reduced density is

$$u \equiv v_c/v; \; v_c = 66.95 \text{ cc.},$$

and the constants are $b_1 = 0.4018$,

$$\begin{array}{ll} c_1 = 0.1085 & e_1 = 0.00321 \\ d_1 = 0.0223 & f_1 = 0.00011. \end{array}$$

Reduced constants for the second term of (1) are

$$\begin{array}{lll} k_1 \equiv A/Rv_c^{m-1} = 40.987 & & k_1k_2 = 0.07621. \\ k_2 \equiv (v_o/v_c)^6 = 0.001860 & & \end{array}$$

The expanded equation then is of the form

$$Pv/RT = 1 + b_1u + c_1u^2 + \cdots - \frac{k_1}{T}u^{m-1}[1 - k_2u^6]. \qquad (3)$$

For approximations it is recognized that m differs but slightly from 2. (The constant k_1 is a function of m.) Combining similar terms,

$$Pv/RT = 1 + (b_1 - k_1 u^{m-2}/T)\,u + c_1 u^2 + \ldots + k_1 k_2 u^{m+5}/T. \quad (4)$$

The more useful form of state and virial equations, respectively, then, are

$$(z - 1)/u = (v_1 - k_1 u^{m-2}/T) + c_1 u + d_1 u^2 + \ldots + k_1 k_2 u^{m+4}/T. \quad (5)$$

$$(z - 1)/u = B_1 + C_1 u + D_1 u^2 + \ldots, \quad (6)$$

where the conventional virial coefficients B_1, C_1, $D_1 \ldots$ are in reduced form. No simple comparison between coefficients of equations (5) and (6) is possible since the coefficients of the latter must be temperature-dependent, whereas for the former they are not.

R. D. G.

APPENDIX III

Improved Temperature-Control Technique

Improved temperature control of the PVT pipet has been achieved in practice by means of appreciable simplification of technique and required apparatus. The control thermocouple between refrigerant tank and pipet is not used. The bucking circuit for this thermocouple is not used. Instead, we are using the platinum resistance thermometer for control as well as measurement. Output signal of the electronic galvanometer, used with the microvolt potentiometer for reading the platinum thermometer, is connected directly to the power regulator for pipet heating temperature control. When it is required to standardize the potentiometer, the steady-state heating current first is carefully adjusted on the power-regulator. The galvanometer signal then is disconnected from the power regulator during the potentiometer standardizing procedures, including thermometer current standardization.

D. E. D.

APPENDIX IV

Potentiometer Battery Stabilization*

Drift rate under a few parts per million per hour is desired in the main working battery for a microvolt potentiometer. The history of our observations follows.

1) Nickel-cadmium alkaline batteries were said to be absolutely trouble-free. Our 4-amp.-hour Gulton cells exude caustic. Their use at full charge, maintained by trickle-charging (Report 2, page 2, and Report 11, figure 1), is unsatisfactory.

2) Mercury batteries, e.g., Mallory RM-42R, while excellent for 1 milliampere circuits, are unsatisfactory at the 5 ma.-level for the main potentiometer battery.

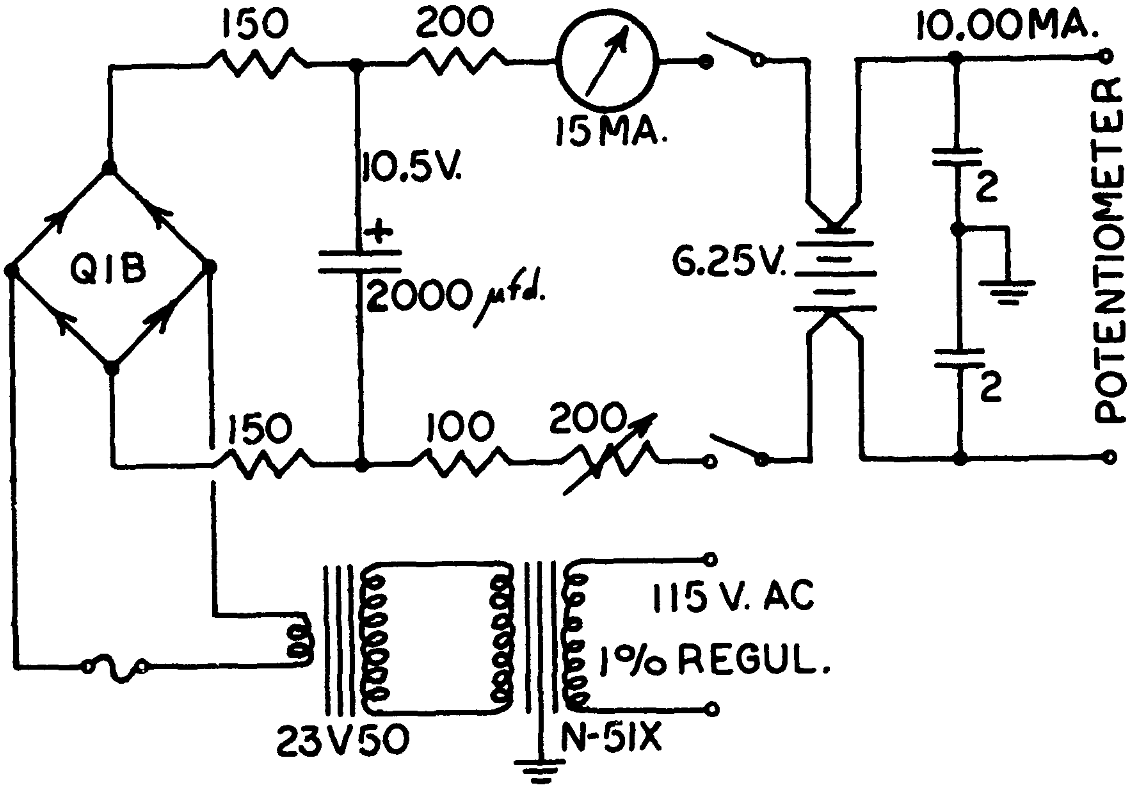
3) Nickel-cadmium cells used in single- or in two-stage circuits as recommended by E. E. Watson (Report 2, page 2), merely as stabilizers across another power source at 50 percent of capacity charge are quite unsatisfactory. Investigation shows that effective internal resistance of 0.1 ohm for a 6-volt battery at one ampere rises into the range 1 to 10 ohms at charge-discharge rates in the sub-milliampere level, accompanied by intolerable hysteresis effects.

4) A conventional, 100-amp.-hour, low-discharge type of lead-acid battery in our figure 3 stabilization circuit is giving satisfaction. The battery is thermally and electrostatically shielded. The two-microfarad condensers greatly reduce noise which otherwise appears in the electronic galvanometer amplifier used with the potentiometer when the rectifier power source is connected to the battery.

*See R. J. Corruccini, Stabilization of a d.c. current source by means of a parallel-connected battery, NBS/CEL Lab Note 60-12, October 13, 1960.

The ten-turn helical rheostat permits any effective battery drift to be adjusted to zero. Our battery is stable under a charging current of about 0.7 milliampere. The manufacturer claims a self-discharge rate of less than 15 percent per year or 1.7 milliampere.

R. D. G.



STABILIZED BATTERY FOR
MICROVOLT POTENTIOMETER

FIGURE 3

APPENDIX V

Pressure Correction for Fluid in Pipet Capillary

From page 26, Report 12, the number of gram-moles of hydrogen in our transition capillary is

$$N_x = PV_xS/RT_o.$$

The dimensionless integral, $0 < S \leqslant 1$, page 43, Report 12, will be taken here as unity. Pressure due to the capillary column then is

$$P_x \leqslant 10^{-3} \cdot N_xM/A,$$

where hydrogen mol. wt. is $M = 2$ and capillary area is $A = 10^{-3}cm^2$ The conversion factor shown is 10^{-3} atm./(g/ cm²). Relative error is

$$P_x/P \leqslant 10^{-3}V_xM/ART_o,$$

reducing, with above values, to

$$P_x/P \leqslant 2\,V_x/RT_o = (16/T_o) \cdot 10^{-4},$$

where T_o is pipet temperature. This correction is not applied by our routine computation, page 19, Report 15.

R. D. G.

APPENDIX VI

Isochore for n-Hydrogen, Run No. 2

It is convenient to compare this experimental result with the data of Stewart and Johnson and with our equation of state, provided the data be interpolated to a true isochore. For data of Exhibit VIII in Report 15, an arbitrary mean molal volume of 30.6 cc. is selected. The required interpolation of pressures to this constant density is obtained by linear interpolation of Stewart and Johnson's data between $v = 30.0$ and $v = 31.0$,

$$-\Delta P/\Delta v = 0.475\,T - 1.4. \qquad \text{(a)}$$

Data of S. and J. at $v = 30.6$ was computed by

$$P_{SJ} = 7.19\,T - 171.2. \qquad \text{(b)}$$

Our equation of state at this density is

$$P_{calc.} = 7.1594\,T - 171.55. \qquad \text{(c)}$$

The second column of table 1 gives the experimental pressures corrected to a constant volume of 30.6, $P_{30.6}$, by means of equation (a). A deviation plot of

$$(P_{30.6} - P_{calc.})/P_{30.6}$$

vs. temperature shows that this isochore in the compressed liquid region curves toward the critical isochore with increasing temperature.

R. D. G.

Table 1

Isochores for n-Hydrogen, Run No. 2

at v = 30.6 cc./mol, Appendix VI

T°K	$P_{30.6}$	P_{SJ}	$P_{calc.}$
28	29.001	30.1	28.91
30	43.558	44.5	43.23
32	58.027	58.9	57.55
34	72.492	73.3	71.87
36	86.999	87.6	86.19
40	115.878	116.4	114.83
45	151.365	152.4	150.62
50	186.369	188.3	186.42
55	220.996	(224.3)	222.22
60	255.180	(260.2)	258.01
65	288.967	(296.2)	293.81

APPENDIX VII

Vapor Pressure Observations, Parahydrogen

The purified hydrogen used for the PVT measurements was converted to the para form by passing slowly over a ferric oxide catalyst at about 19.6°K. The efficiency of the conversion was checked in several cases when the sample was cooled below the point where the isochore intersects the vapor pressure curve. The resulting vapor pressures were compared with values for 20.5°K-equilibrium hydrogen, e-H_2, from the literature. The table following illustrates the agreement of our data with that of Hoge and Arnold [1]. The corresponding vapor pressures for normal hydrogen, from White, Friedman, and Johnston [2], are included for comparison.

L. A. W.

References

[1] H. J. Hoge and R. D. Arnold, J. Res. NBS 42, 63 (1951).

[2] D. White, A. S. Friedman, and H. L. Johnston, J. Am. Chem. Soc. 72, 3927 (1950).

Table 2

Vapor Pressure Observations

Run	T, °K	P(this work) (atm.)	$e\text{-}H_2$[1] (atm.)	$n\text{-}H_2$[2] (atm.)
5	26	3.9811	3.9777	3.8249
6	27	4.8215	4.8226	4.6296
14	30	8.1041	8.1087	7.7786
25	32	11.051	11.033	10.630

APPENDIX VIII

PVT Data for Parahydrogen

Tables 3 through 31 present experimental results in the range 28 through 70 cc/g. mol. The following limitations should be carefully considered relative to any utilization of these data:

1) A small, indeterminate, but not insignificant error exists in the temperatures, as described below. Some of these experiments therefore will be repeated.
2) These data have not been smoothed.
3) The initial point of a few runs falls on the vapor pressure curve.

These tables have been computed from laboratory "input" observations as described by Exhibits VI and VII of Report 15. This laboratory has changed from an IBM-650 computing machine to a CDC-1604 during the course of the experiments. The latter was used to print out the data tables. Greater flexibility of the latter computer is reflected by our revised laboratory data sheets, Exhibits A and B.

Temperature Error. Initial measurements purportedly showed absence of significant spurious potentials from the platinum thermometer measuring circuit when the thermometer current was off. After the PVT measurements were completed, a spurious residual potential was found which drifted from 0.36 to 0.24 microvolt in eight hours under conditions used for PVT measurements. This potential was of the same sign as those produced for measurement by the one milliampere thermometer current. Temperatures given by tables 3 through 31 therefore are higher than the true temperature. The following table illustrates the magnitude of the error, which must be regarded as indeterminate.

Temperature Error Corresponding to 0.3 Microvolt Residual Signal on Platinum Thermometer Measured with One Milliampere Current

T	dR/dT	Error, °K
15	.0081	0.0370
20	.0186	0.0161
25	.0329	0.0091
30	.0483	0.0062
35	.0632	0.0047
40	.0761	0.0039
60	.1045	0.0029
100	.1102	0.0027

If the temperature error be ignored, a corresponding error in pressures may be considered. Rough values for the worst condition (occurring at a low pressure of 5 atm. and an isochore slope of 10 atm. per degree) yield at about 17°K an error in the order of 6 percent in pressure.

Three examinations for self-consistency or mistakes have been performed.

1) The laboratory P vs. T data for each run is difference prior to any PVT computation as in Exhibit IV, Report 15. A plot of these first differences in the form

$$\Delta P/\Delta T \text{ vs. } \bar{T} \equiv (T_2 + T_1)/2$$

affords a sensitivity of examination equal to or greater than the precision of measurement of these variables. A few early runs were repeated because of inadequate smoothness in these plots.

2) For each run, the PVT computation is carried out to obtain the nearly constant density at each temperature. Each of these densities depends upon numerous small apparatus corrections, such as the temperature of the external null-detector diaphragm. Any erroneously-recorded laboratory data will produce irregularities in some order of

the differences of these densities within a single run, Exhibit V, Report 51, detected usually by a plot of $\Delta v/\Delta T$ vs. $\bar{T}$.

3) Self-consistency of the density between different runs at different densities is equivalent to such consistency in measurements of the amount of gas released from the pipet at the end of each run. After the PVT computations for a set of numerous runs are complete, it is required to plot and examine for smoothness a suitable type of isotherm containing one point from every run. To ask for an isotherm linear in density is to ask for an equation of state. We have found adequate sensitivity for the present purpose, despite the curvature at high densities, by using the value of the second virial coefficient, B, for normal hydrogen together with our parahydrogen data $Z \equiv Pv/RT$ and plotting

$$[(Z - 1)v - B]v \ \underline{\text{vs.}} \ 1/v.$$

The results in tables 3 through 31 were so examined on the 60°K isotherm.

H. M. R. and R. D. G.

PVT Measurements of Hydrogen
Pressure – Temperature Data ; Data Cards .

Page: ______

Pressure in psi.				Piston
NPD	.	P	50.	Hi
	.	O	100.	
	.	N	200.	Lo
X	0.5	M	200.	
W	1.0	L	500.	
V	2.0	A	1000.	
U	2.0	B	1000.	
T	5.0	C	1000.	
S	10.0	D	1000.	
R	20.0	E	1000.	
Q	20.0		30.	

Dead Weight Gage Temp. °C	Diaphragm Temp. °C	Barometer in mm Hg.	Barometer Temp. °C	Pipet Temp. Pt. Thermom. Resistance, Ω / Temp., in °K	Integral $T_0\int_0^1 \frac{dx}{T_x Z_x}$	Identification Run No. Point No.
12	18	24	32	38 .000	48	55 58

2

Pressure in atm:
Guard-ring 125 Ω, current ma:
Pipet heater 550 Ω, current ma:
Reflux gage reading: ; gas is:
Remarks:

Reader:

Recorder:

Date:

Time (start):

EXHIBIT A

PVT Measurements of Hydrogen
Gasometry Data ; Header Card

Page: ______

Total Volume Used	Waterbath	Mercury - Manometer		Manifold	Pipet Temp. Pt. Thermom.	Diaphragm	Identification
Volume 994.11 2036.72 6426.97 21225.95	Temp. °C	Temp. °C	Reading in mm. Hg. U L	Temp. °C	Resistance, Ω Temp., in °K .0.0.0	Temp. °C	Run No. Point No.
1	12	18	24	32	38	47	55 – 59

Hydrogen condition: normal, para

Remarks:

Reader:

Recorder:

Date:

Time (start):

EXHIBIT B

Table 3

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
29.934860	+.033405869	+8.393305	+24.000	+.1275802	00301
29.943599	+.033396119	+15.891936	+25.000	+.2319664	00302
29.951941	+.033386818	+23.356666	+26.000	+.3279041	00303
29.960372	+.033377423	+30.833169	+27.000	+.4169519	00304
29.968711	+.033368136	+38.275522	+28.000	+.4992471	00305
29.976951	+.033358963	+45.718093	+29.000	+.5759197	00306
29.985302	+.033349673	+53.160814	+30.000	+.6475349	00307
29.993552	+.033340499	+60.569494	+31.000	+.7141748	00308
30.001530	+.033331633	+67.978389	+32.000	+.7766917	00309
30.009486	+.033322796	+75.319103	+33.000	+.8347071	00310
30.017184	+.033314251	+82.693009	+34.000	+.8897012	00311
30.025045	+.033305528	+90.067742	+35.000	+.9416061	00312
30.032639	+.033297107	+97.386484	+36.000	+.9900886	00313
30.039998	+.033288950	+104.682082	+37.000	+1.0357499	00314
30.047409	+.033280740	+111.956297	+38.000	+1.0788382	00315
30.054580	+.033272799	+119.228459	+39.000	+1.1197224	00316
30.061644	+.033264981	+126.501739	+40.000	+1.1586002	00317
30.076220	+.033248859	+140.844244	+42.000	+1.2291289	00318
30.090307	+.033233293	+155.153287	+44.000	+1.2930618	00319
30.104190	+.033217967	+169.393839	+46.000	+1.3509867	00320
30.117364	+.033203438	+183.532815	+48.000	+1.4033752	00321
30.129908	+.033189613	+197.569451	+50.000	+1.4508816	00322
30.160366	+.033156096	+232.273372	+55.000	+1.5522358	00323
30.190107	+.033123433	+266.401649	+60.000	+1.6335585	00324
30.218593	+.033092209	+300.123158	+65.000	+1.7003752	00325
30.245509	+.033062760	+333.267506	+70.000	+1.7548508	00326

Table 4

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
31.038374	+.032218182	+4.514691	+25.000	+.0683080	00401
31.047270	+.032208951	+11.527084	+26.000	+.1677467	00402
31.055983	+.032199915	+18.528051	+27.000	+.2597141	00403
31.064432	+.032191157	+25.500267	+28.000	+.3447740	00404
31.073006	+.032182274	+32.462027	+29.000	+.4238823	00405
31.081414	+.032173569	+39.400403	+30.000	+.4974673	00406
31.089887	+.032164801	+46.322578	+31.000	+.5661539	00407
31.098200	+.032156202	+53.232738	+32.000	+.6304468	00408
31.106489	+.032147633	+60.126805	+33.000	+.6907002	00409
31.114558	+.032139296	+66.997137	+34.000	+.7471802	00410
31.122523	+.032131071	+73.874055	+35.000	+.8005400	00411
31.130517	+.032122820	+80.716590	+36.000	+.8506110	00412
31.138373	+.032114716	+87.548116	+37.000	+.8978946	00413
31.146069	+.032106781	+94.356725	+38.000	+.9424903	00414
31.153523	+.032099098	+101.148642	+39.000	+.9846616	00415
31.161126	+.032091267	+107.912362	+40.000	+1.0244923	00416
31.175754	+.032076209	+121.377228	+42.000	+1.0979669	00417
31.190177	+.032061376	+134.768783	+44.000	+1.1642301	00418
31.204615	+.032046542	+148.092606	+46.000	+1.2242743	00419
31.218161	+.032032637	+161.314407	+48.000	+1.2785673	00420
31.232082	+.032018358	+174.468363	+50.000	+1.3281037	00421
31.264049	+.031985620	+206.998148	+55.000	+1.4339479	00422
31.295713	+.031953258	+239.087611	+60.000	+1.5197601	00423
31.325588	+.031922784	+270.701633	+65.000	+1.5898682	00424
31.353794	+.031894066	+301.841772	+70.000	+1.6476151	00425
31.380792	+.031866627	+332.438291	+75.000	+1.6951106	00426

Table 5

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
32.047618	+.031203567	+3.981079	+26.000	+.0598009	00501
32.056272	+.031195144	+10.307247	+27.000	+.1491339	00502
32.065146	+.031186510	+16.855061	+28.000	+.2352285	00503
32.073901	+.031177997	+23.397134	+29.000	+.3153558	00504
32.082544	+.031169598	+29.916232	+30.000	+.3898870	00505
32.091040	+.031161346	+36.440665	+31.000	+.4597193	00506
32.098976	+.031153641	+42.931637	+32.000	+.5248111	00507
32.107270	+.031145594	+49.416859	+33.000	+.5859343	00508
32.115509	+.031137604	+55.868228	+34.000	+.6431098	00509
32.123417	+.031129938	+62.352869	+35.000	+.6974202	00510
32.131537	+.031122072	+68.815960	+36.000	+.7485185	00511
32.139234	+.031114618	+75.250287	+37.000	+.7965744	00512
32.147174	+.031106934	+81.662641	+38.000	+.8419126	00513
32.154755	+.031099600	+88.051862	+39.000	+.8847152	00514
32.162405	+.031092202	+94.440936	+40.000	+.9254078	00515
32.177812	+.031077315	+107.162910	+42.000	+1.0005438	00516
32.192497	+.031063138	+119.787714	+44.000	+1.0680673	00517
32.207136	+.031049020	+132.354246	+46.000	+1.1293187	00518
32.221459	+.031035218	+144.856845	+48.000	+1.1850245	00519
32.235632	+.031021572	+157.266170	+50.000	+1.2356227	00520
32.269942	+.030988590	+187.894894	+55.000	+1.3434912	00521
32.302020	+.030957816	+218.215962	+60.000	+1.4316911	00522
32.332861	+.030928287	+248.059574	+65.000	+1.5037344	00523
32.362719	+.030899752	+277.531633	+70.000	+1.5636654	00524
32.391334	+.030872455	+306.527815	+75.000	+1.6133249	00525

Table 6

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
33.038165	+.030268024	+4.821450	+27.000	+.0718976	00601
33.046523	+.030260370	+10.593140	+28.000	+.1523621	00602
33.055445	+.030252202	+16.750673	+29.000	+.2326814	00603
33.064060	+.030244319	+22.885178	+30.000	+.3073786	00604
33.072661	+.030236454	+28.996976	+31.000	+.3770027	00605
33.081234	+.030228618	+35.125624	+32.000	+.4425274	00606
33.089703	+.030220881	+41.231945	+33.000	+.5038452	00607
33.098134	+.030213184	+47.349012	+34.000	+.5617200	00608
33.106493	+.030205555	+53.460745	+35.000	+.6162607	00609
33.114455	+.030198292	+59.538419	+36.000	+.6674162	00610
33.122601	+.030190866	+65.615380	+37.000	+.7158347	00611
33.130498	+.030183669	+71.670072	+38.000	+.7614941	00612
33.138290	+.030176573	+77.713122	+39.000	+.8047189	00613
33.146239	+.030169335	+83.740590	+40.000	+.8456578	00614
33.161527	+.030155427	+95.737629	+42.000	+.9211965	00615
33.176909	+.030141446	+107.684270	+44.000	+.9895093	00616
33.191588	+.030128115	+119.534233	+46.000	+1.0511068	00617
33.205968	+.030115068	+131.343206	+48.000	+1.1073040	00618
33.220222	+.030102147	+143.125930	+50.000	+1.1588713	00619
33.254961	+.030070701	+172.219857	+55.000	+1.2689992	00620
33.287733	+.030041096	+200.806143	+60.000	+1.3576703	00621
33.319599	+.030012366	+229.154665	+65.000	+1.4315268	00622
33.350674	+.029984402	+257.096192	+70.000	+1.4927483	00623
33.379572	+.029958443	+284.630758	+75.000	+1.5437810	00624
33.407653	+.029933261	+311.820935	+80.000	+1.5868856	00625

Table 7

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
34.045596	+.029372375	+6.034199	+28.000	+.0894143	00701
34.054380	+.029364798	+11.765978	+29.000	+.1683788	00702
34.062965	+.029357398	+17.532097	+30.000	+.2425936	00703
34.071478	+.029350062	+23.286886	+31.000	+.3119070	00704
34.080064	+.029342668	+29.058030	+32.000	+.3771386	00705
34.088585	+.029335333	+34.823768	+33.000	+.4383845	00706
34.097043	+.029328056	+40.584443	+34.000	+.4960001	00707
34.105425	+.029320849	+46.327866	+35.000	+.5501512	00708
34.113601	+.029313821	+52.076339	+36.000	+.6013812	00709
34.121722	+.029306844	+57.813936	+37.000	+.6497498	00710
34.129795	+.029299912	+63.546471	+38.000	+.6955461	00711
34.138014	+.029292858	+69.255912	+39.000	+.7387795	00712
34.145749	+.029286222	+74.971007	+40.000	+.7799277	00713
34.161583	+.029272648	+86.293101	+42.000	+.8553604	00714
34.177283	+.029259201	+97.605272	+44.000	+.9239373	00715
34.192272	+.029246375	+108.820597	+46.000	+.9857473	00716
34.207032	+.029233755	+120.002482	+48.000	+1.0421944	00717
34.221485	+.029221408	+131.116217	+50.000	+1.0936280	00718
34.256962	+.029191147	+158.651896	+55.000	+1.2042476	00719
34.291229	+.029161976	+185.809253	+60.000	+1.2941467	00720
34.323022	+.029134964	+212.627332	+65.000	+1.3682820	00721
34.354411	+.029108344	+239.106247	+70.000	+1.4300781	00722
34.385512	+.029082016	+265.246674	+75.000	+1.4820011	00723
34.414438	+.029057572	+291.081431	+80.000	+1.5259825	00724
34.442627	+.029033790	+316.678639	+85.000	+1.5637974	00725

Table 8

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
35.124695	+.028469998	+7.925239	+29.000	+.1169799	00801
35.133437	+.028462914	+13.289257	+30.000	+.1896638	00802
35.141927	+.028456038	+18.686724	+31.000	+.2581555	00803
35.150532	+.028449072	+24.084269	+32.000	+.3224035	00804
35.158913	+.028442290	+29.487748	+33.000	+.3828666	00805
35.167392	+.028435432	+34.902456	+34.000	+.4399483	00806
35.175817	+.028428622	+40.305820	+35.000	+.4936604	00807
35.184358	+.028421721	+45.703366	+36.000	+.5443518	00808
35.192408	+.028415219	+51.123337	+37.000	+.5925852	00809
35.200472	+.028408710	+56.504169	+38.000	+.6378664	00810
35.208650	+.028402111	+61.896337	+39.000	+.6809796	00811
35.216733	+.028395593	+67.254204	+40.000	+.7215939	00812
35.232458	+.028382919	+77.964559	+42.000	+.7970310	00813
35.248414	+.028370071	+88.590971	+44.000	+.8648897	00814
35.263845	+.028357657	+99.166049	+46.000	+.9264441	00815
35.278656	+.028345751	+109.763872	+48.000	+.9831382	00816
35.293178	+.028334087	+120.254542	+50.000	+1.0344431	00817
35.329857	+.028304672	+146.311260	+55.000	+1.1453581	00818
35.364161	+.028277215	+172.006725	+60.000	+1.2354976	00819
35.398125	+.028250084	+197.431065	+65.000	+1.3102880	00820
35.429793	+.028224833	+222.483386	+70.000	+1.3723110	00821
35.461742	+.028199404	+247.230396	+75.000	+1.4245741	00822
35.491774	+.028175543	+271.706429	+80.000	+1.4690007	00823
35.521590	+.028151893	+295.944809	+85.000	+1.5071919	00824
35.550016	+.028129383	+319.912095	+90.000	+1.5399702	00825
35.577224	+.028107870	+343.642912	+95.000	+1.5683400	00826

Table 9

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
29.489722	+.033910120	+6.356789	+23.000	+.0993265	00901
29.498587	+.033899928	+14.099720	+24.000	+.2111956	00902
29.507210	+.033890022	+21.803063	+25.000	+.3136101	00903
29.515560	+.033880434	+29.483780	+26.000	+.4078920	00904
29.524093	+.033870643	+37.164752	+27.000	+.4952545	00905
29.532483	+.033861020	+44.817373	+28.000	+.5760666	00906
29.540798	+.033851489	+52.458924	+29.000	+.6512204	00907
29.549024	+.033842065	+60.066627	+30.000	+.7210070	00908
29.556848	+.033833107	+67.662632	+31.000	+.7861939	00909
29.564843	+.033823958	+75.236077	+32.000	+.8471028	00910
29.572821	+.033814833	+82.809612	+33.000	+.9043654	00911
29.580626	+.033805910	+90.292602	+34.000	+.9573373	00912
29.588064	+.033797412	+97.855409	+35.000	+1.0081327	00913
29.595355	+.033789086	+105.395226	+36.000	+1.0559087	00914
29.602943	+.033780425	+112.895160	+37.000	+1.1007606	00915
29.610036	+.033772334	+120.360977	+38.000	+1.1429452	00916
29.617487	+.033763837	+127.804791	+39.000	+1.1828103	00917
29.624419	+.033755937	+135.248482	+40.000	+1.2206934	00918
29.638474	+.033739929	+150.034444	+42.000	+1.2902738	00919
29.652690	+.033723754	+164.707687	+44.000	+1.3527254	00920
29.666163	+.033708437	+179.290233	+46.000	+1.4091089	00921
29.679341	+.033693471	+193.810820	+48.000	+1.4604120	00922
29.692253	+.033678818	+208.171138	+50.000	+1.5065309	00923
29.723383	+.033643546	+243.819937	+55.000	+1.6057914	00924
29.753022	+.033610032	+278.835250	+60.000	+1.6850464	00925
29.780762	+.033578724	+313.409402	+65.000	+1.7499226	00926
29.806785	+.033549408	+347.510658	+70.000	+1.8033067	00927

Table 10

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
29.011196	+.034469452	+5.186625	+22.000	+.0833513	01001
29.020201	+.034458755	+13.104905	+23.000	+.2015073	01002
29.028559	+.034448834	+21.018091	+24.000	+.3098075	01003
29.037014	+.034438803	+28.897120	+25.000	+.4090260	01004
29.045321	+.034428953	+36.781948	+26.000	+.5007511	01005
29.053693	+.034419032	+44.649648	+27.000	+.5855176	01006
29.061975	+.034409224	+52.512281	+28.000	+.6642206	01007
29.069893	+.034399852	+60.363417	+29.000	+.7374008	01008
29.077971	+.034390295	+68.186449	+30.000	+.8054253	01009
29.086020	+.034380779	+76.020228	+31.000	+.8692328	01010
29.093943	+.034371415	+83.831795	+32.000	+.9288503	01011
29.101444	+.034362556	+91.632576	+33.000	+.9847701	01012
29.109218	+.034353379	+99.404783	+34.000	+1.0371541	01013
29.116495	+.034344793	+107.177101	+35.000	+1.0865693	01014
29.124116	+.034335806	+114.915713	+36.000	+1.1329586	01015
29.131202	+.034327454	+122.615022	+37.000	+1.1764805	01016
29.138915	+.034318368	+130.372269	+38.000	+1.2183144	01017
29.145846	+.034310206	+138.082908	+39.000	+1.2575821	01018
29.153126	+.034301639	+145.759264	+40.000	+1.2946300	01019
29.166916	+.034285421	+160.897293	+42.000	+1.3616777	01020
29.180443	+.034269527	+175.978198	+44.000	+1.4222713	01021
29.193694	+.034253973	+190.968835	+46.000	+1.4769918	01022
29.206731	+.034238683	+205.925684	+48.000	+1.5269914	01023
29.219452	+.034223777	+220.713291	+50.000	+1.5718638	01024
29.249936	+.034188109	+257.382832	+55.000	+1.6681157	01025
29.279187	+.034153954	+293.464691	+60.000	+1.7452111	01026
29.306332	+.034122318	+329.027123	+65.000	+1.8078574	01027

Table 11

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
28.532854	+.035047318	+4.888002	+21.000	+.0809360	01101
28.541633	+.035036538	+13.015339	+22.000	+.2057766	01102
28.550087	+.035026163	+21.148898	+23.000	+.3199276	01103
28.558501	+.035015843	+29.276083	+24.000	+.4245428	01104
28.566707	+.035005785	+37.375879	+25.000	+.5204703	01105
28.574992	+.034995635	+45.486660	+26.000	+.6092299	01106
28.583195	+.034985592	+53.586338	+27.000	+.6913301	01107
28.590988	+.034976056	+61.658135	+28.000	+.7672659	01108
28.599000	+.034966258	+69.746568	+29.000	+.8382239	01109
28.606936	+.034956557	+77.806560	+30.000	+.9041712	01110
28.614737	+.034947027	+85.838499	+31.000	+.9655940	01111
28.622502	+.034937547	+93.876404	+32.000	+1.0232893	01112
28.629762	+.034928687	+101.902560	+33.000	+1.0773908	01113
28.636915	+.034919963	+109.889575	+34.000	+1.1279456	01114
28.644007	+.034911317	+117.910627	+35.000	+1.1759884	01115
28.651375	+.034902339	+125.863273	+36.000	+1.2207489	01116
28.658215	+.034894009	+133.816760	+37.000	+1.2631132	01117
28.665576	+.034885049	+141.771174	+38.000	+1.3033149	01118
28.672322	+.034876840	+149.690680	+39.000	+1.3411501	01119
28.679418	+.034868211	+157.542284	+40.000	+1.3765496	01120
28.693471	+.034851134	+173.178435	+42.000	+1.4418231	01121
28.706723	+.034835045	+188.780305	+44.000	+1.5009700	01122
28.719054	+.034820089	+204.212968	+46.000	+1.5537458	01123
28.731194	+.034805376	+219.612021	+48.000	+1.6019646	01124
28.743590	+.034790366	+234.874904	+50.000	+1.6454776	01125
28.774117	+.034753456	+272.609147	+55.000	+1.7380573	01126
28.802477	+.034719236	+309.700148	+60.000	+1.8117754	01127
28.828965	+.034687336	+346.349010	+65.000	+1.8720352	01128

Table 12

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
28.033716	+.035671333	+5.785051	+20.000	+.0988194	01201
28.042362	+.035660334	+14.054182	+21.000	+.2287100	01202
28.050667	+.035649776	+22.340841	+22.000	+.3471398	01203
28.058974	+.035639222	+30.667200	+23.000	+.4559345	01204
28.067152	+.035628838	+39.022417	+24.000	+.5561419	01205
28.075410	+.035618358	+47.366142	+25.000	+.6482440	01206
28.083271	+.035608388	+55.710081	+26.000	+.7333183	01207
28.091352	+.035598144	+64.052749	+27.000	+.8121402	01208
28.099335	+.035588031	+72.402607	+28.000	+.8854756	01209
28.106906	+.035578445	+80.719003	+29.000	+.9534001	01210
28.114721	+.035568555	+89.035419	+30.000	+1.0168566	01211
28.122430	+.035558805	+97.300090	+31.000	+1.0756940	01212
28.130150	+.035549046	+105.610694	+32.000	+1.1313952	01213
28.137256	+.035540069	+113.847586	+33.000	+1.1829762	01214
28.144510	+.035530909	+122.140436	+34.000	+1.2321359	01215
28.151998	+.035521458	+130.391255	+35.000	+1.2781270	01216
28.158858	+.035512803	+138.616841	+36.000	+1.3213349	01217
28.165580	+.035504329	+146.774163	+37.000	+1.3616044	01218
28.172772	+.035495265	+154.966166	+38.000	+1.4001264	01219
28.179860	+.035486337	+163.090136	+39.000	+1.4361053	01220
28.186360	+.035478154	+171.214290	+40.000	+1.4702912	01221
28.199586	+.035461514	+187.291908	+42.000	+1.5324871	01222
28.212636	+.035445111	+203.404729	+44.000	+1.5894117	01223
28.225303	+.035429204	+219.347127	+46.000	+1.6402011	01224
28.237704	+.035413644	+235.188054	+48.000	+1.6861173	01225
28.249942	+.035398303	+250.961225	+50.000	+1.7279793	01226
28.278918	+.035362031	+289.952890	+55.000	+1.8168200	01227
28.306078	+.035328102	+328.267062	+60.000	+1.8872964	01228

Table 13

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
36.141178	+.027669270	+10.438232	+30.000	+.1532471	01301
36.149944	+.027662560	+15.513648	+31.000	+.2204673	01302
36.158543	+.027655982	+20.599968	+32.000	+.2836690	01303
36.167030	+.027649492	+25.697848	+33.000	+.3432259	01304
36.175624	+.027642924	+30.795808	+34.000	+.3993127	01305
36.184141	+.027636417	+35.893371	+35.000	+.4522190	01306
36.192652	+.027629918	+41.008092	+36.000	+.5024257	01307
36.200822	+.027623682	+46.100089	+37.000	+.5496710	01308
36.209198	+.027617292	+51.197960	+38.000	+.5945280	01309
36.217499	+.027610963	+56.290240	+39.000	+.6370468	01310
36.225757	+.027604668	+61.365277	+40.000	+.6772742	01311
36.241738	+.027592495	+71.493503	+42.000	+.7518145	01312
36.258252	+.027579929	+81.576006	+44.000	+.8192208	01313
36.273782	+.027568120	+91.636359	+46.000	+.8806173	01314
36.289058	+.027556516	+101.651593	+48.000	+.9365544	01315
36.304134	+.027545072	+111.615570	+50.000	+.9876322	01316
36.341082	+.027517068	+136.359406	+55.000	+1.0980058	01317
36.377394	+.027489600	+160.769830	+60.000	+1.1878709	01318
36.411567	+.027463800	+184.937123	+65.000	+1.2625090	01319
36.444639	+.027438878	+208.833310	+70.000	+1.3250118	01320
36.476878	+.027414627	+232.389594	+75.000	+1.3773916	01321
36.507600	+.027391557	+255.742369	+80.000	+1.4222644	01322
36.538258	+.027368573	+278.858684	+85.000	+1.4608225	01323
36.567374	+.027346782	+301.703979	+90.000	+1.4938833	01324
36.595792	+.027325546	+324.276356	+95.000	+1.5223244	01325

Table 14

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
37.420867	+.026723058	+8.104123	+30.000	+.1231921	01401
37.429134	+.026717156	+12.573387	+31.000	+.1850055	01402
37.437814	+.026710961	+17.274255	+32.000	+.2462885	01403
37.446507	+.026704760	+22.009625	+33.000	+.3043648	01404
37.454817	+.026698836	+26.756542	+34.000	+.3592056	01405
37.463408	+.026692713	+31.519373	+35.000	+.4111508	01406
37.471873	+.026686683	+36.265898	+36.000	+.4600295	01407
37.480132	+.026680803	+41.034874	+37.000	+.5065669	01408
37.488539	+.026674819	+45.781435	+38.000	+.5504130	01409
37.496879	+.026668886	+50.539670	+39.000	+.5921712	01410
37.505226	+.026662951	+55.297208	+40.000	+.6318578	01411
37.521722	+.026651229	+64.756685	+42.000	+.7050216	01412
37.538103	+.026639598	+74.227047	+44.000	+.7717314	01413
37.554269	+.026628131	+83.641602	+46.000	+.8321626	01414
37.569843	+.026617093	+93.033374	+48.000	+.8874038	01415
37.585117	+.026606276	+102.368567	+50.000	+.9377712	01416
37.622786	+.026579637	+125.616445	+55.000	+1.0471747	01417
37.658683	+.026554301	+148.582248	+60.000	+1.1364888	01418
37.694714	+.026528918	+171.332727	+65.000	+1.2108540	01419
37.728648	+.026505058	+193.800970	+70.000	+1.2729564	01420
37.761748	+.026481825	+215.996998	+75.000	+1.3253266	01421
37.793282	+.026459729	+237.956552	+80.000	+1.3699561	01422
37.824921	+.026437596	+259.814434	+85.000	+1.4089862	01423
37.855469	+.026416262	+281.396489	+90.000	+1.4424115	01424
37.885087	+.026395610	+302.710825	+95.000	+1.4711502	01425
37.913888	+.026375559	+323.822401	+100.000	+1.4961997	01426

Table 15

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
38.148772	+.026213163	+11.351019	+31.000	+.1702308	01501
38.157475	+.026207185	+15.866023	+32.000	+.2305590	01502
38.166058	+.026201291	+20.409017	+33.000	+.2876536	01503
38.174547	+.026195465	+24.974553	+34.000	+.3417252	01504
38.183175	+.026189546	+29.545815	+35.000	+.3928116	01505
38.191790	+.026183638	+34.128294	+36.000	+.4412314	01506
38.200335	+.026177781	+38.711164	+37.000	+.4870640	01507
38.208870	+.026171933	+43.298657	+38.000	+.5305660	01508
38.217374	+.026166110	+47.887375	+39.000	+.5718757	01509
38.225473	+.026160566	+52.453412	+40.000	+.6108731	01510
38.242222	+.026149108	+61.613310	+42.000	+.6836798	01511
38.258020	+.026138310	+70.727896	+44.000	+.7494539	01512
38.275123	+.026126631	+79.814076	+46.000	+.8093244	01513
38.290970	+.026115818	+88.900817	+48.000	+.8642617	01514
38.306650	+.026105128	+97.948193	+50.000	+.9145026	01515
38.345028	+.026079000	+120.387342	+55.000	+1.0228491	01516
38.379653	+.026055473	+142.583887	+60.000	+1.1114876	01517
38.419490	+.026028456	+164.611096	+65.000	+1.1857188	01518
38.455118	+.026004341	+186.367725	+70.000	+1.2477029	01519
38.488395	+.025981858	+207.852132	+75.000	+1.2998923	01520
38.521503	+.025959527	+229.099989	+80.000	+1.3443819	01521
38.553272	+.025938136	+250.177193	+85.000	+1.3828478	01522
38.585014	+.025916798	+271.085241	+90.000	+1.4163363	01523
38.615510	+.025896330	+291.754761	+95.000	+1.4452417	01524
38.645399	+.025876302	+312.187202	+100.000	+1.4702705	01525

Table 16

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
39.076967	+.025590523	+10.179018	+31.000	+.1563685	01601
39.085590	+.025584877	+14.444805	+32.000	+.2150120	01602
39.094255	+.025579206	+18.749517	+33.000	+.2706908	01603
39.102719	+.025573669	+23.077010	+34.000	+.3234387	01604
39.111188	+.025568131	+27.432810	+35.000	+.3735835	01605
39.119809	+.025562497	+31.788438	+36.000	+.4209667	01606
39.128399	+.025556885	+36.161656	+37.000	+.4660398	01607
39.136944	+.025551305	+40.540173	+38.000	+.5088307	01608
39.145490	+.025545727	+44.912838	+39.000	+.5493789	01609
39.153957	+.025540203	+49.285351	+40.000	+.5879195	01610
39.170443	+.025529453	+58.025641	+42.000	+.6594980	01611
39.187123	+.025518587	+66.754961	+44.000	+.7245337	01612
39.203639	+.025507836	+75.452115	+46.000	+.7836540	01613
39.220023	+.025497180	+84.156223	+48.000	+.8379869	01614
39.235782	+.025486940	+92.823523	+50.000	+.8876765	01615
39.274501	+.025461813	+114.304569	+55.000	+.9947087	01616
39.312236	+.025437372	+135.581877	+60.000	+1.0825863	01617
39.349112	+.025413534	+156.691843	+65.000	+1.1559854	01618
39.384383	+.025390775	+177.563169	+70.000	+1.2174840	01619
39.418871	+.025368560	+198.197311	+75.000	+1.2694776	01620
39.452519	+.025346924	+218.627344	+80.000	+1.3139341	01621
39.485061	+.025326034	+238.888688	+85.000	+1.3523647	01622
39.518256	+.025304761	+259.014813	+90.000	+1.3860032	01623
39.549978	+.025284464	+278.902613	+95.000	+1.4150103	01624
39.579406	+.025265664	+298.514356	+100.000	+1.4398553	01625

Table 17

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
40.013640	+.024991478	+13.307865	+32.000	+.2027920	01701
40.022179	+.024986146	+17.403341	+33.000	+.2572194	01702
40.030831	+.024980746	+21.521359	+34.000	+.3087946	01703
40.039287	+.024975470	+25.661639	+35.000	+.3577561	01704
40.047923	+.024970084	+29.830265	+36.000	+.4044073	01705
40.056532	+.024964717	+34.004691	+37.000	+.4486367	01706
40.065117	+.024959368	+38.184978	+38.000	+.4906364	01707
40.073701	+.024954021	+42.370866	+39.000	+.5305747	01708
40.081921	+.024948904	+46.551081	+40.000	+.5684636	01709
40.098898	+.024938341	+54.934321	+42.000	+.6391625	01710
40.115667	+.024927916	+63.283896	+44.000	+.7031353	01711
40.132365	+.024917545	+71.633327	+46.000	+.7616166	01712
40.148838	+.024907321	+79.960374	+48.000	+.8150625	01713
40.164781	+.024897435	+88.253232	+50.000	+.8639535	01714
40.204599	+.024872776	+108.896206	+55.000	+.9700858	01715
40.242294	+.024849478	+129.335065	+60.000	+1.0571391	01716
40.279683	+.024826412	+149.594069	+65.000	+1.1297216	01717
40.316025	+.024804033	+169.679100	+70.000	+1.1909469	01718
40.351193	+.024782414	+189.502550	+75.000	+1.2424947	01719
40.385472	+.024761379	+209.150628	+80.000	+1.2867042	01720
40.418355	+.024741234	+228.595315	+85.000	+1.3246813	01721
40.451441	+.024720998	+247.939089	+90.000	+1.3580659	01722
40.483749	+.024701270	+267.044526	+95.000	+1.3868362	01723
40.515492	+.024681917	+285.945454	+100.000	+1.4118504	01724

Table 18

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
41.904243	+.023863932	+11.830375	+32.000	+.1887952	01801
41.912859	+.023859026	+15.512208	+33.000	+.2400995	01802
41.921420	+.023854154	+19.262003	+34.000	+.2894296	01803
41.930079	+.023849227	+23.022889	+35.000	+.3361258	01804
41.938604	+.023844379	+26.835050	+36.000	+.3809766	01805
41.947292	+.023839441	+30.652927	+37.000	+.4235050	01806
41.955970	+.023834510	+34.481765	+38.000	+.4639637	01807
41.964616	+.023829600	+38.310647	+39.000	+.5023686	01808
41.973230	+.023824709	+42.150886	+40.000	+.5390182	01809
41.990094	+.023815141	+49.837536	+42.000	+.6072094	01810
42.007147	+.023805473	+57.524185	+44.000	+.6692762	01811
42.024087	+.023795877	+65.205316	+46.000	+.7259519	01812
42.040909	+.023786355	+72.875031	+48.000	+.7778466	01813
42.05756	+.023776933	+80.532932	+50.000	+.8255284	01814
42.097671	+.023754283	+99.543819	+55.000	+.9285260	01815
42.136855	+.023732194	+118.418850	+60.000	+1.0134821	01816
42.175148	+.023710646	+137.158703	+65.000	+1.0845535	01817
42.212649	+.023689582	+155.740033	+70.000	+1.1445353	01818
42.249407	+.023668971	+174.095336	+75.000	+1.1951732	01819
42.284665	+.023649236	+192.315068	+80.000	+1.2387697	01820
42.318764	+.023630180	+210.364741	+85.000	+1.2763546	01821
42.352889	+.023611140	+228.278738	+90.000	+1.3091529	01822
42.385706	+.023592859	+246.023027	+95.000	+1.3376914	01823
42.418931	+.023574380	+263.633090	+100.000	+1.3628373	01824

Table 19

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
43.975859	+.022739749	+11.038638	+32.000	+.1848690	01901
43.984272	+.022735399	+14.301159	+33.000	+.2322946	01902
43.992948	+.022730916	+17.682248	+34.000	+.2788213	01903
44.001697	+.022726396	+21.114470	+35.000	+.3234938	01904
44.010293	+.022721957	+24.580921	+36.000	+.3662134	01905
44.019034	+.022717445	+28.058876	+37.000	+.4068117	01906
44.027823	+.022712911	+31.565241	+38.000	+.4456943	01907
44.036456	+.022708458	+35.071573	+39.000	+.4826000	01908
44.045100	+.022704001	+38.588878	+40.000	+.5178263	01909
44.062590	+.022694989	+45.635789	+42.000	+.5834594	01910
44.079908	+.022686073	+52.693508	+44.000	+.6433236	01911
44.096534	+.022677519	+59.746083	+46.000	+.6979759	01912
44.113928	+.022668577	+66.797596	+48.000	+.7481345	01913
44.130878	+.022659871	+73.838629	+50.000	+.7942195	01914
44.172391	+.022638575	+91.359485	+55.000	+.8941826	01915
44.212474	+.022618051	+108.760584	+60.000	+.9766736	01916
44.251852	+.022597924	+126.055907	+65.000	+1.0458410	01917
44.290578	+.022578165	+143.215196	+70.000	+1.1042992	01918
44.327853	+.022559179	+160.177249	+75.000	+1.1537206	01919
44.365248	+.022540165	+176.980767	+80.000	+1.1960886	01920
44.401638	+.022521692	+193.706840	+85.000	+1.2331315	01921
44.437529	+.022503502	+210.298360	+90.000	+1.2653995	01922
44.471998	+.022486059	+226.718243	+95.000	+1.2934030	01923
44.506646	+.022468554	+242.935541	+100.000	+1.3176507	01924

Table 20

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
46.273168	+.021610796	+13.547137	+33.000	+.2314980	02001
46.281849	+.021606742	+16.600027	+34.000	+.2753753	02002
46.290707	+.021602608	+19.715513	+35.000	+.3177739	02003
46.299619	+.021598450	+22.873114	+36.000	+.3584962	02004
46.308565	+.021594277	+26.047429	+37.000	+.3972911	02005
46.317509	+.021590108	+29.238921	+38.000	+.4343175	02006
46.326504	+.021585915	+32.442328	+39.000	+.4696359	02007
46.335491	+.021581729	+35.659577	+40.000	+.5034013	02008
46.353063	+.021573548	+42.108926	+42.000	+.5663536	02009
46.370862	+.021565267	+48.575048	+44.000	+.6238642	02010
46.388620	+.021557011	+55.043888	+46.000	+.6764677	02011
46.406352	+.021548774	+61.513195	+48.000	+.7247510	02012
46.423478	+.021540825	+67.971150	+50.000	+.7690891	02013
46.466303	+.021520972	+84.054158	+55.000	+.8654042	02014
46.507544	+.021501888	+100.067762	+60.000	+.9452587	02015
46.548599	+.021482924	+115.974205	+65.000	+1.0121364	02016
46.588503	+.021464523	+131.773609	+70.000	+1.0687928	02017
46.627406	+.021446615	+147.404003	+75.000	+1.1167954	02018
46.666637	+.021428585	+162.903631	+80.000	+1.1580616	02019
46.704294	+.021411307	+178.319344	+85.000	+1.1940450	02020
46.740905	+.021394537	+193.639415	+90.000	+1.2255548	02021
46.777514	+.021377793	+208.804428	+95.000	+1.2529611	02022
46.813525	+.021361348	+223.831032	+100.000	+1.2769562	02023

Table 21

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
48.182428	+.020754454	+13.208837	+33.000	+.2350302	02101
48.191179	+.020750685	+16.041176	+34.000	+.2770826	02102
48.200134	+.020746830	+18.929689	+35.000	+.3176933	02103
48.209158	+.020742947	+21.864133	+36.000	+.3568155	02104
48.218214	+.020739051	+24.826366	+37.000	+.3942820	02105
48.227182	+.020735195	+27.799890	+38.000	+.4299676	02106
48.236256	+.020731294	+30.796351	+39.000	+.4641866	02107
48.245182	+.020727458	+33.792425	+40.000	+.4967040	02108
48.263363	+.020719650	+39.813743	+42.000	+.5575524	02109
48.281478	+.020711876	+45.852528	+44.000	+.6131624	02110
48.299458	+.020704166	+51.902297	+46.000	+.6641335	02111
48.317334	+.020696506	+57.946217	+48.000	+.7108389	02112
48.334937	+.020688969	+63.990107	+50.000	+.7538559	02113
48.378736	+.020670238	+79.047428	+55.000	+.8473521	02114
48.421551	+.020651961	+94.035872	+60.000	+.9248374	02115
48.463542	+.020634067	+108.951474	+65.000	+.9899637	02116
48.504859	+.020616491	+123.749059	+70.000	+1.0449932	02117
48.544626	+.020599602	+138.410736	+75.000	+1.0917773	02118
48.584522	+.020582687	+152.970145	+80.000	+1.1321370	02119
48.623339	+.020566255	+167.439044	+85.000	+1.1672583	02120
48.661451	+.020550147	+181.823882	+90.000	+1.1980580	02121
48.699348	+.020534156	+196.089476	+95.000	+1.2250059	02122
48.736506	+.020518500	+210.172210	+100.000	+1.2482859	02123

Table 22

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
50.392609	+.019844180	+15.600956	+34.000	+.2817887	02201
50.401543	+.019840662	+18.274383	+35.000	+.3207029	02202
50.410664	+.019837072	+20.993113	+36.000	+.3582458	02203
50.419846	+.019833460	+23.740597	+37.000	+.3942537	02204
50.428884	+.019829906	+26.498581	+38.000	+.4285512	02205
50.437979	+.019826330	+29.279474	+39.000	+.4614671	02206
50.447207	+.019822703	+32.066265	+40.000	+.4928445	02207
50.465672	+.019815450	+37.662638	+42.000	+.5514954	02208
50.484033	+.019808243	+43.275516	+44.000	+.6051012	02209
50.502470	+.019801012	+48.900436	+46.000	+.6542623	02210
50.520753	+.019793846	+54.524967	+48.000	+.6993722	02211
50.538511	+.019786891	+60.144187	+50.000	+.7408503	02212
50.583752	+.019769194	+74.164378	+55.000	+.8312431	02213
50.627888	+.019751960	+88.110773	+60.000	+.9060495	02214
50.670904	+.019735192	+102.005807	+65.000	+.9690687	02215
50.713236	+.019718718	+115.816432	+70.000	+1.0225342	02216
50.754899	+.019702532	+129.497236	+75.000	+1.0679762	02217
50.795395	+.019686824	+143.070293	+80.000	+1.1070524	02218
50.836276	+.019670992	+156.592808	+85.000	+1.1413293	02219
50.875904	+.019655670	+169.996982	+90.000	+1.1711033	02220
50.915777	+.019640278	+183.309754	+95.000	+1.1972882	02221
50.953611	+.019625694	+196.510205	+100.000	+1.2202377	02222

Table 23

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
55.315576	+.018078091	+12.831355	+33.000	+.2621141	02301
55.324787	+.018075081	+15.074417	+34.000	+.2989274	02302
55.334087	+.018072043	+17.385402	+35.000	+.3349607	02303
55.343495	+.018068971	+19.735999	+36.000	+.3697495	02304
55.353141	+.018065822	+22.109337	+37.000	+.4030887	02305
55.362782	+.018062676	+24.505168	+38.000	+.4350873	02306
55.372230	+.018059594	+26.895275	+39.000	+.4653586	02307
55.381787	+.018056478	+29.297102	+40.000	+.4943289	02308
55.401149	+.018050167	+34.139889	+42.000	+.5488023	02309
55.420450	+.018043881	+38.983248	+44.000	+.5983837	02310
55.439734	+.018037605	+43.837646	+46.000	+.6438651	02311
55.459007	+.018031336	+48.703324	+48.000	+.6857626	02312
55.478269	+.018025076	+53.563411	+50.000	+.7242783	02313
55.525422	+.018009769	+65.685670	+55.000	+.8081355	02314
55.571916	+.017994701	+77.735686	+60.000	+.8774228	02315
55.619561	+.017979286	+89.800021	+65.000	+.9364293	02316
55.664115	+.017964895	+101.761698	+70.000	+.9861568	02317
55.708132	+.017950701	+113.626185	+75.000	+1.0285375	02318
55.751683	+.017936678	+125.420694	+80.000	+1.0651765	02319
55.795268	+.017922667	+137.147851	+85.000	+1.0971141	02320
55.838807	+.017908692	+148.835652	+90.000	+1.1253431	02321
55.881977	+.017894857	+160.431997	+95.000	+1.1500680	02322
55.923040	+.017881717	+171.921238	+100.000	+1.1716683	02323

Table 24

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
61.057276	+.016378064	+14.787962	+34.000	+.3236318	02401
61.067305	+.016375375	+16.812647	+35.000	+.3574877	02402
61.077456	+.016372653	+18.857553	+36.000	+.3898954	02403
61.087337	+.016370005	+20.924978	+37.000	+.4210162	02404
61.097485	+.016367286	+22.998222	+38.000	+.4506282	02405
61.108087	+.016364446	+25.077099	+39.000	+.4788459	02406
61.118212	+.016361735	+27.158653	+40.000	+.5057120	02407
61.138292	+.016356361	+31.338835	+42.000	+.5559442	02408
61.159078	+.016350802	+35.530149	+44.000	+.6018519	02409
61.179174	+.016345432	+39.724734	+46.000	+.6438595	02410
61.199533	+.016339994	+43.922410	+48.000	+.6824603	02411
61.219830	+.016334576	+48.113707	+50.000	+.7179188	02412
61.269738	+.016321271	+58.575671	+55.000	+.7952157	02413
61.319950	+.016307906	+69.003976	+60.000	+.8594271	02414
61.369345	+.016294780	+79.410198	+65.000	+.9136898	02415
61.417570	+.016281986	+89.748115	+70.000	+.9596310	02416
61.465678	+.016269242	+100.012459	+75.000	+.9988721	02417
61.512573	+.016256839	+110.226191	+80.000	+1.0328638	02418
61.559314	+.016244496	+120.393687	+85.000	+1.0625832	02419
61.605599	+.016232291	+130.505788	+90.000	+1.0886589	02420
61.652290	+.016219998	+140.549710	+95.000	+1.1115780	02421
61.697769	+.016208042	+150.509200	+100.000	+1.1316624	02422

Table 25

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
65.914422	+.015171187	+11.050651	+32.000	+.2773976	02501
65.935240	+.015166397	+14.630665	+34.000	+.3457698	02502
65.945906	+.015163944	+16.476605	+35.000	+.3783310	02503
65.956473	+.015161514	+18.328512	+36.000	+.4092291	02504
65.967212	+.015159046	+20.192284	+37.000	+.4387289	02505
65.977992	+.015156569	+22.061592	+38.000	+.4668063	02506
65.988756	+.015154097	+23.930735	+39.000	+.4934529	02507
65.999226	+.015151693	+25.805594	+40.000	+.5188921	02508
66.020518	+.015146806	+29.554908	+42.000	+.5661658	02509
66.042012	+.015141877	+33.316281	+44.000	+.6094085	02510
66.063468	+.015136959	+37.077060	+46.000	+.6489230	02511
66.084920	+.015132045	+40.842943	+48.000	+.6852713	02512
66.106196	+.015127175	+44.592837	+50.000	+.7184915	02513
66.159256	+.015115043	+53.944017	+55.000	+.7907798	02514
66.211730	+.015103064	+63.307890	+60.000	+.8513848	02515
66.264047	+.015091140	+72.620446	+65.000	+.9022105	02516
66.314817	+.015079586	+81.887345	+70.000	+.9453958	02517
66.365745	+.015068014	+91.081247	+75.000	+.9821912	02518
66.416075	+.015056596	+100.235180	+80.000	+1.0141163	02519
66.465108	+.015045488	+109.374301	+85.000	+1.0422561	02520
66.515659	+.015034054	+118.454763	+90.000	+1.0668866	02521
66.564121	+.015023108	+127.445085	+95.000	+1.0882384	02522
66.612226	+.015012259	+136.396020	+100.000	+1.1072355	02523

Table 26

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
70.731455	+.014137981	+14.496689	+34.000	+.3675250	02601
70.742407	+.014135793	+16.195715	+35.000	+.3989296	02602
70.753766	+.014133523	+17.894997	+36.000	+.4286108	02603
70.765044	+.014131271	+19.594115	+37.000	+.4566959	02604
70.776337	+.014129016	+21.299215	+38.000	+.4834510	02605
70.787692	+.014126750	+23.004367	+39.000	+.5088477	02606
70.798994	+.014124494	+24.709010	+40.000	+.5329750	02607
70.820981	+.014120109	+28.118918	+42.000	+.5778241	02608
70.844193	+.014115483	+31.534162	+44.000	+.6187529	02609
70.866374	+.014111065	+34.949916	+46.000	+.6561647	02610
70.888518	+.014106657	+38.359474	+48.000	+.6903855	02611
70.910913	+.014102202	+41.775007	+50.000	+.7220113	02612
70.966789	+.014091098	+50.260257	+55.000	+.7903174	02613
71.021577	+.014080228	+58.728308	+60.000	+.8471707	02614
71.077284	+.014069193	+67.168716	+65.000	+.8950945	02615
71.130995	+.014058569	+75.569664	+70.000	+.9358208	02616
71.184763	+.014047950	+83.902862	+75.000	+.9704807	02617
71.237886	+.014037474	+92.204527	+80.000	+1.0005934	02618
71.290873	+.014027041	+100.472562	+85.000	+1.0269442	02619
71.341978	+.014016993	+108.697339	+90.000	+1.0500402	02620
71.394192	+.014006742	+116.876471	+95.000	+1.0704114	02621
71.445343	+.013996713	+124.994387	+100.000	+1.0883004	02622

Table 27

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
37.084659	+.026965328	+8.463938	+30.000	+.1275058	02701
37.093295	+.026959050	+13.224701	+31.000	+.1928430	02702
37.102015	+.026952714	+18.030196	+32.000	+.2547606	02703
37.110545	+.026946519	+22.845014	+33.000	+.3130828	02704
37.119186	+.026940246	+27.681812	+34.000	+.3682972	02705
37.127560	+.026934170	+32.519167	+35.000	+.4203898	02706
37.136119	+.026927962	+37.367709	+36.000	+.4697587	02707
37.144620	+.026921799	+42.217017	+37.000	+.5164950	02708
37.152879	+.026915814	+47.057931	+38.000	+.5606942	02709
37.161268	+.026909738	+51.897125	+39.000	+.6026339	02710
37.169499	+.026903780	+56.722995	+40.000	+.6423478	02711
37.186013	+.026891831	+66.378456	+42.000	+.7162124	02712
37.202355	+.026880019	+75.994002	+44.000	+.7830355	02713
37.218550	+.026868322	+85.572720	+46.000	+.8437646	02714
37.234281	+.026856971	+95.123194	+48.000	+.8992336	02715
37.249574	+.026845945	+104.634344	+50.000	+.9499701	02716
37.286510	+.026819351	+128.217876	+55.000	+1.0593074	02717
37.323651	+.026792663	+151.529492	+60.000	+1.1487206	02718
37.359201	+.026767168	+174.626565	+65.000	+1.2231477	02719
37.393067	+.026742926	+197.435071	+70.000	+1.2852917	02720
37.426099	+.026719322	+219.973241	+75.000	+1.3377271	02721
37.457666	+.026696805	+242.274102	+80.000	+1.3824266	02722
37.489427	+.026674187	+264.359039	+85.000	+1.4209160	02723
37.519867	+.026652546	+286.287284	+90.000	+1.4544715	02724
37.549249	+.026631691	+307.909541	+95.000	+1.4831503	02725
37.578345	+.026611071	+329.295289	+100.000	+1.5080215	02726

Table 28

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
29.009195	+.034471829	+5.213951	+22.000	+.0837846	02801
29.018031	+.034461332	+13.075567	+23.000	+.2010412	02802
29.026567	+.034451198	+20.974556	+24.000	+.3091445	02803
29.035055	+.034441127	+28.869577	+25.000	+.4086085	02804
29.043561	+.034431040	+36.754313	+26.000	+.5003446	02805
29.051759	+.034421324	+44.644749	+27.000	+.5854144	02806
29.060068	+.034411482	+52.523979	+28.000	+.6643250	02807
29.067973	+.034402123	+60.391440	+29.000	+.7376944	02808
29.076199	+.034392391	+68.242240	+30.000	+.8060352	02809
29.084372	+.034382727	+76.065085	+31.000	+.8696965	02810
29.091978	+.034373737	+83.887175	+32.000	+.9294012	02811
29.099834	+.034364457	+91.687455	+33.000	+.9853054	02812
29.107211	+.034355748	+99.464879	+34.000	+1.0377095	02813
29.114649	+.034346971	+107.231273	+35.000	+1.0870496	02814
29.122039	+.034338255	+114.969551	+36.000	+1.1334085	02815
29.129348	+.034329639	+122.718464	+37.000	+1.1773981	02816
29.136602	+.034321092	+130.417373	+38.000	+1.2186391	02817
29.143486	+.034312985	+138.093194	+39.000	+1.2575740	02818
29.150755	+.034304428	+145.729402	+40.000	+1.2942595	02819
29.164542	+.034288212	+160.940776	+42.000	+1.3619348	02820
29.178113	+.034272264	+176.050020	+44.000	+1.4227381	02821
29.191254	+.034256836	+191.062947	+46.000	+1.4775962	02822
29.203990	+.034241896	+205.986287	+48.000	+1.5272974	02823
29.217022	+.034226624	+220.824586	+50.000	+1.5725256	02824
29.247445	+.034191021	+257.419521	+55.000	+1.6682114	02825
29.276481	+.034157111	+293.489840	+60.000	+1.7451994	02826
29.303090	+.034126094	+329.017451	+65.000	+1.8076043	02827

Table 29

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
29.479576	+.033921790	+6.275642	+23.000	+.0980248	02901
29.488471	+.033911558	+13.978759	+24.000	+.2093119	02902
29.496985	+.033901770	+21.668113	+25.000	+.3115610	02903
29.505311	+.033892203	+29.337984	+26.000	+.4057341	02904
29.513801	+.033882454	+37.002270	+27.000	+.4929174	02905
29.522176	+.033872841	+44.642662	+28.000	+.5736207	02906
29.530488	+.033863307	+52.278703	+29.000	+.6487566	02907
29.538655	+.033853945	+59.891225	+30.000	+.7186493	02908
29.546820	+.033844590	+67.499049	+31.000	+.7840271	02909
29.554526	+.033835765	+75.078293	+32.000	+.8450313	02910
29.562475	+.033826667	+82.657622	+33.000	+.9023897	02911
29.570371	+.033817634	+90.216970	+34.000	+.9562038	02912
29.577755	+.033809192	+97.765295	+35.000	+1.0068534	02913
29.585249	+.033800628	+105.294013	+36.000	+1.0545344	02914
29.592709	+.033792107	+112.805489	+37.000	+1.0995060	02915
29.599812	+.033783998	+120.288279	+38.000	+1.1418605	02916
29.607269	+.033775490	+127.743853	+39.000	+1.1818384	02917
29.614212	+.033767571	+135.165087	+40.000	+1.2195204	02918
29.628216	+.033751610	+149.951295	+42.000	+1.2891124	02919
29.642486	+.033735362	+164.646110	+44.000	+1.3517544	02920
29.656562	+.033719351	+179.240462	+46.000	+1.4082618	02921
29.669226	+.033704958	+193.743864	+48.000	+1.4594099	02922
29.682184	+.033690243	+208.157166	+50.000	+1.5059189	02923
29.712755	+.033655580	+243.749411	+55.000	+1.6047529	02924
29.742855	+.033621520	+278.799811	+60.000	+1.6842565	02925
29.770697	+.033590077	+313.409053	+65.000	+1.7493292	02926
29.798102	+.033559185	+347.475867	+70.000	+1.8026009	02927

Table 30

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
28.064174	+.035632618	+5.568598	+20.000	+.0952253	03001
28.072888	+.035621558	+13.878514	+21.000	+.2260972	03002
28.081174	+.035611047	+22.215941	+22.000	+.3455745	03003
28.089493	+.035600500	+30.548201	+23.000	+.4546593	03004
28.098078	+.035589623	+38.897335	+24.000	+.5549701	03005
28.106146	+.035579407	+47.229655	+25.000	+.6470836	03006
28.114344	+.035569032	+55.573707	+26.000	+.7323326	03007
28.122146	+.035559164	+63.900413	+27.000	+.8110969	03008
28.130107	+.035549101	+72.209783	+28.000	+.8840845	03009
28.137987	+.035539144	+80.514226	+29.000	+.9520330	03010
28.145808	+.035529269	+88.807081	+30.000	+1.0153702	03011
28.153120	+.035520042	+97.077482	+31.000	+1.0744042	03012
28.160369	+.035510899	+105.336744	+32.000	+1.1296726	03013
28.167926	+.035501372	+113.590725	+33.000	+1.1815937	03014
28.174918	+.035492561	+121.821269	+34.000	+1.2302439	03015
28.182315	+.035483245	+130.041249	+35.000	+1.2760689	03016
28.189178	+.035474606	+138.227267	+36.000	+1.3190401	03017
28.195912	+.035466134	+146.395859	+37.000	+1.3595575	03018
28.203033	+.035457179	+154.548401	+38.000	+1.3978517	03019
28.209586	+.035448943	+162.666360	+39.000	+1.4338846	03020
28.216575	+.035440163	+170.739133	+40.000	+1.4677826	03021
28.230393	+.035422815	+186.845180	+42.000	+1.5305020	03022
28.242696	+.035407385	+202.794701	+44.000	+1.5863333	03023
28.255406	+.035391458	+218.652409	+46.000	+1.6367500	03024
28.267830	+.035375903	+234.436450	+48.000	+1.6825219	03025
28.279966	+.035360722	+250.141589	+50.000	+1.7241663	03026
28.309766	+.035323500	+288.828608	+55.000	+1.8117495	03027
28.336155	+.035290603	+326.905782	+60.000	+1.8814671	03028

Table 31

VOL CC/MOL	1/V	PRESS ATM	T DEG K	Z = PV/RT	IDENT
30.020111	+.033311003	+7.455760	+24.000	+.1136521	03101
30.029026	+.033301114	+14.926629	+25.000	+.2184979	03102
30.037537	+.033291677	+22.378146	+26.000	+.3150645	03103
30.046010	+.033282290	+29.801173	+27.000	+.4041483	03104
30.054528	+.033272856	+37.212754	+28.000	+.4867748	03105
30.062939	+.033263548	+44.607293	+29.000	+.5635386	03106
30.071268	+.033254334	+51.982332	+30.000	+.6349954	03107
30.079473	+.033245263	+59.340403	+31.000	+.7016869	03108
30.087520	+.033236372	+66.693149	+32.000	+.7641911	03109
30.095395	+.033227675	+74.022693	+33.000	+.8226884	03110
30.103368	+.033218874	+81.329977	+34.000	+.8775486	03111
30.111253	+.033210176	+88.631534	+35.000	+.9292518	03112
30.118900	+.033201744	+95.910710	+36.000	+.9778857	03113
30.126259	+.033193634	+103.184172	+37.000	+1.0238608	03114
30.133823	+.033185301	+110.412238	+38.000	+1.0670192	03115
30.140832	+.033177584	+117.629501	+39.000	+1.1078762	03116
30.148324	+.033169339	+124.817927	+40.000	+1.1464748	03117
30.162636	+.033153601	+139.133458	+42.000	+1.2176878	03118
30.176835	+.033138001	+153.347317	+44.000	+1.2816858	03119
30.190877	+.033122589	+167.476112	+46.000	+1.3395383	03120
30.204346	+.033107819	+181.520444	+48.000	+1.3919964	03121
30.217565	+.033093335	+195.485477	+50.000	+1.4397541	03122
30.248712	+.033059259	+229.954688	+55.000	+1.5412420	03123
30.278818	+.033026388	+263.961078	+60.000	+1.6233491	03124
30.307702	+.032994913	+297.424319	+65.000	+1.6900537	03125
30.335098	+.032965116	+330.448608	+70.000	+1.7451616	03126

1.2 Thermal Conductivity of Fluids

William J. Hall

1.2 Thermal Conductivity of Fluids

Since the pressure in the thermal conductivity apparatus reaches 300 atmospheres, it was necessary to open the sealed platinum resistance thermometers to the surrounding atmosphere to prevent them from being crushed even though this would also cause them to lose calibration.

To recalibrate the thermometers, the hot plate and the cold plate, each containing a platinum resistance thermometer, were placed in physical contact. The hot plate, cold plate, and block were then in thermal equilibrium. The measuring block could be held at any desired temperature and the two thermometers inside checked against a sealed resistance thermometer with a previous calibration outside the pressure cell.

Unfortunately, we have not received the calibration on the external thermometer; therefore, all the data presented in tables I and II must be relative and is given in terms of resistance as a function of the resistance of the calibrated thermometer rather than a function of temperature.

The calibration was done for 0.1, 1.0, and 10.0 atmospheres with helium gas in the system. The block was brought to a specified temperature and held at that temperature while the readings were taken; then the pressure was changed and the temperature held constant. This was rather easy to accomplish since the heat capacity of the block is many times that of the gas in the system. The temperature can be held to at least ±0.001°K or ±0.0001 ohms on the resistance thermometer. Many times the block was steady to ±0.0001°K.

The resistances of the platinum thermometers were measured by a potentiometric method. A current of 2 milliamperes ±5 microamperes, supplied by three mercury cells in series with 2,000 ohms and measured by a 1-ohm standard resistor, was passed through the thermometers. The apparent voltage on the platinum resistance thermometer was measured both with and without current flowing through it, and the difference between these two measurements was the true voltage on the thermometer. A slight correction to the current was also necessary since the 1-ohm resistor was actually 0.99998 ohms. The ratio of the corrected voltage to the corrected current then gave the resistance of the platinum thermometer.

Preliminary graphs of the data indicate that there is some conduction of heat from the thermometers by the gas. This may mean there will be a slight error produced in the temperature measurement which will be a function of the thermal conductivity of the gas in the system. For this reason, and also to make various other calibration checks on the system, we will measure the thermal conductivity of air first and then check the results of the system against the results of other researchers.

Fortunately, the minor disturbances, such as thermocouple breaks and vacuum failures, which have slowed the progress of the apparatus are becoming less frequent.

Table I

Platinum Resistance Thermometer Calibrations - Hydrogen Range

Standard Resistance (In the block)	Temperature (approx.)	Pressure	Cold Plate Thermometer Resistance	Deviation from Standard	Hot Plate Thermometer Resistance	Deviation from Standard
1.06515Ω	40	0.1 atmos.	1.06764Ω	$+250 \times 10^{-5}\,\Omega$	1.06632Ω	$+117 \times 10^{-5}\,\Omega$
1.06488	40	1.0	1.06738	+251	1.06605	+118
1.06129	40	10.0	1.06366	+237	1.06235	+106
1.92866	50	0.1	1.93150	+285	1.92955	+ 88
1.92848	50	1.0	1.93136	+288	1.92942	+ 95
1.92927	50	10.0	1.93177	+250	1.92983	+ 57
2.92732	60	0.1	2.93052	+320	2.92787	+ 55
2.92729	60	1.0	2.93053	+324	2.92787	+ 58
2.92549	60	10.0	2.92843	+294	2.92577	+ 28
3.99355	70	0.1	3.99719	+364	3.99382	+ 26
3.98297	70	1.0	3.98665	+367	3.98329	+ 32
3.99418	70	10.0	3.99738	+320	3.99400	- 19

Table II

Platinum Resistance Thermometer Calibrations - Nitrogen Range

Standard Resistance (In the block)	Temperature (approx.)	Pressure	Cold Plate Thermometer Resistance	Deviation from Standard	Hot Plate Thermometer Resistance	Deviation from Standard
3.24796Ω	63.4	0.1 atmos.	3.25183Ω	$+387 \times 10^{-5}\Omega$	3.24899Ω	$+103 \times 10^{-5}\Omega$
3.24789	63.4	1.0	3.25176	+387	3.24891	+102
3.25232	63.4	10.0	3.25612	+380	3.25329	+ 96
4.63406	76	0.1	4.63835	+429	4.63448	+ 49
4.64323	76	1.0	4.64762	+439	4.64383	+ 59
4.64428	76	10.0	4.64854	+426	4.64474	+ 46
6.19031	90	0.1	6.19532	+501	6.19057	+ 26
6.19791	90	1.0	6.20289	+498	6.19807	+ 18
6.19087	90	10.0	6.19571	+484	6.19098	+ 10
8.41118	110	0.1	8.41717	+599	8.41100	- 20
8.40911	110	1.0	8.41508	+597	8.40893	- 22
8.41572	110	10.0	8.42145	+573	8.41511	- 55
10.57514	130	0.1	10.58153	+639	10.57408	-106
10.57994	130	1.0	10.58638	+644	10.57895	-107
10.58413	130	10.0	10.59034	+621	10.58280	-133
12.63381	150	0.1	12.64102	+721	12.63220	-161
12.63430	150	1.0	12.64146	+716	12.63261	-169
12.67998	150	10.0	12.68712	+714	12.67823	-175

2. Cryogenic Instrumentation

J. Macinko, P. Smelser, R. C. Muhlenhaupt,
C. E. Miller, Dr. R. B. Jacobs

The main effort of the instrumentation project during the past quarter has been devoted to the design and construction of test apparatus with a secondary effort applied to the survey of flowmeters. Manufacturers have been requested to submit instruments on a consignment basis for testing. Upon completion of testing, the instruments will be returned and results and recommendations will be sent to the manufacturers.

Pressure Transducers

The test apparatus (figure 11, First Quarterly Report), has been built, installed at the test site and the associated control and recording instruments have been checked out. The apparatus has been cold shocked and mock tests have been run. A delay in the shipping of the pressure standards prevented any tests from being performed to date. However the test gages have been installed and preliminary tests are being run while waiting for the dead weight calibration tester. The overall performance will be evaluated after calibration.

Each transducer will be calibrated at temperatures of 300°K, 90°K, 76°K and 20°K. In addition, the temperature bath can be controlled in the ranges of 20 to 33°K and 76 to 100°K. Temperature coefficients in these regions can thus be obtained. Temperature cycling and hysteresis effects will be determined in addition to repeatability, zero shift and linearity.

Temperature Sensors

A test apparatus (figure 1) for determining the response time of temperature sensors has been designed and construction will begin

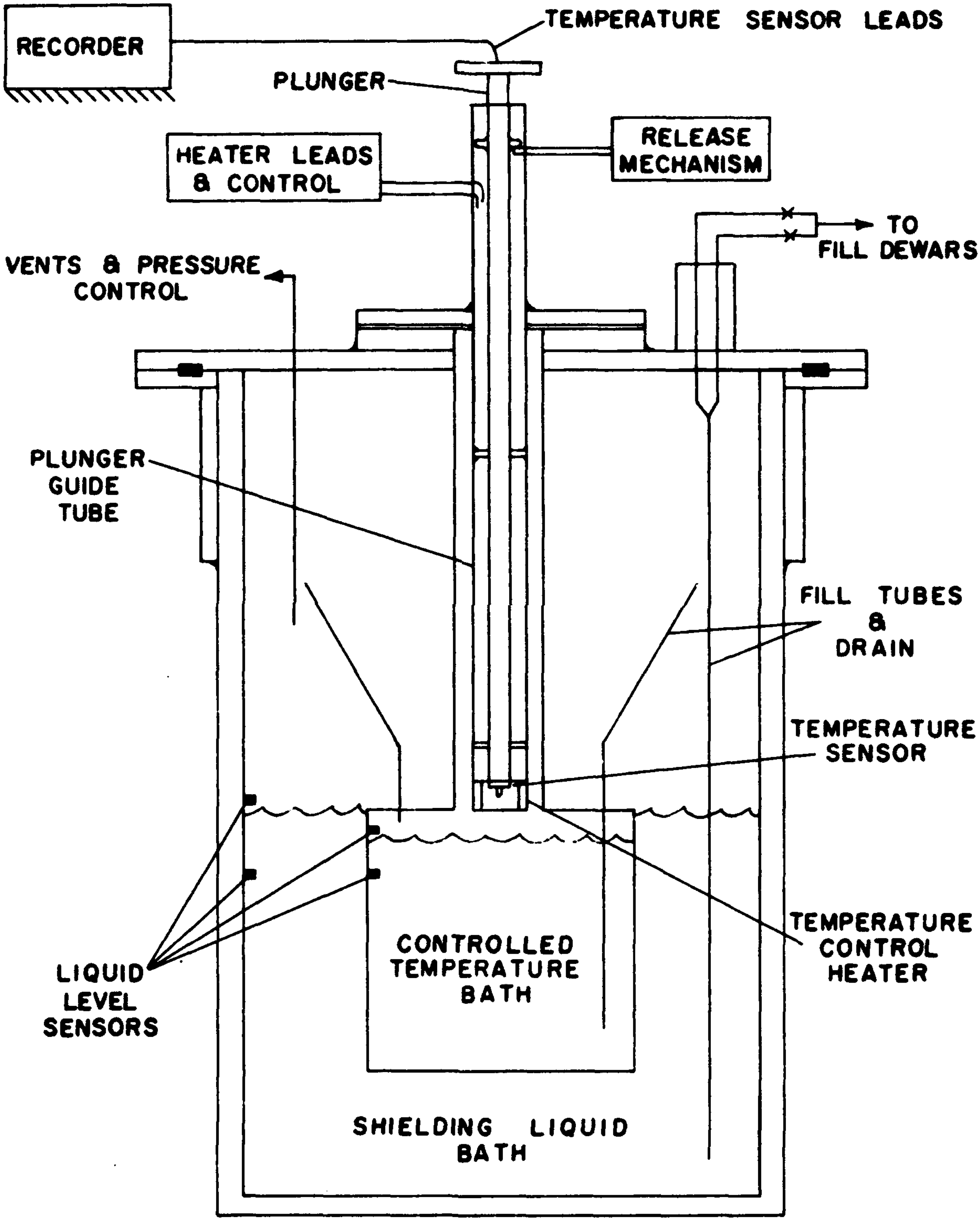


Figure 1

TEMPERATURE SENSOR RESPONSE TESTER

shortly. This unit has a spring loaded plunger which will move a temperature sensor from a controlled temperature in the vapor region into a controlled liquid bath. This will give the response time for sensors subjected to a vapor to liquid change in surroundings. As designed, the test chamber will accommodate sensors up to 3/4" in diameter and up to 20" in length.

A second unit is being designed to utilize the rapid change in liquid temperature brought about by adiabatic compression. With the sensor submerged, a temperature step function can be obtained in the ambient liquid and the response time determined. Several basic design problems must be resolved before the overall design takes its final form. Two apparatuses concerned with the dynamic characteristics of temperature sensors are being used in an effort to obtain data directly applicable to actual situations, and to ascertain the feasibility of describing characteristics independent from the heat transfer characteristics of the test fluids.

Liquid Level Gages

The instrumentation program will include the calibration and evaluation of liquid level gages. Present plans call for a primary standard capable of accurately following a changing liquid level. Several ideas for a standard are being investigated and tested. As soon as a decision is made on the standard, design of the test apparatus will begin.

Tests have just been completed on a transistor liquid level indicator using carbon resistors as sensing elements. A schematic of the circuit is given in figure 2. Factors affecting choice of resistor size, type of liquid, stability, reliability, and other considerations are discussed in a paper which is undergoing final revision and will

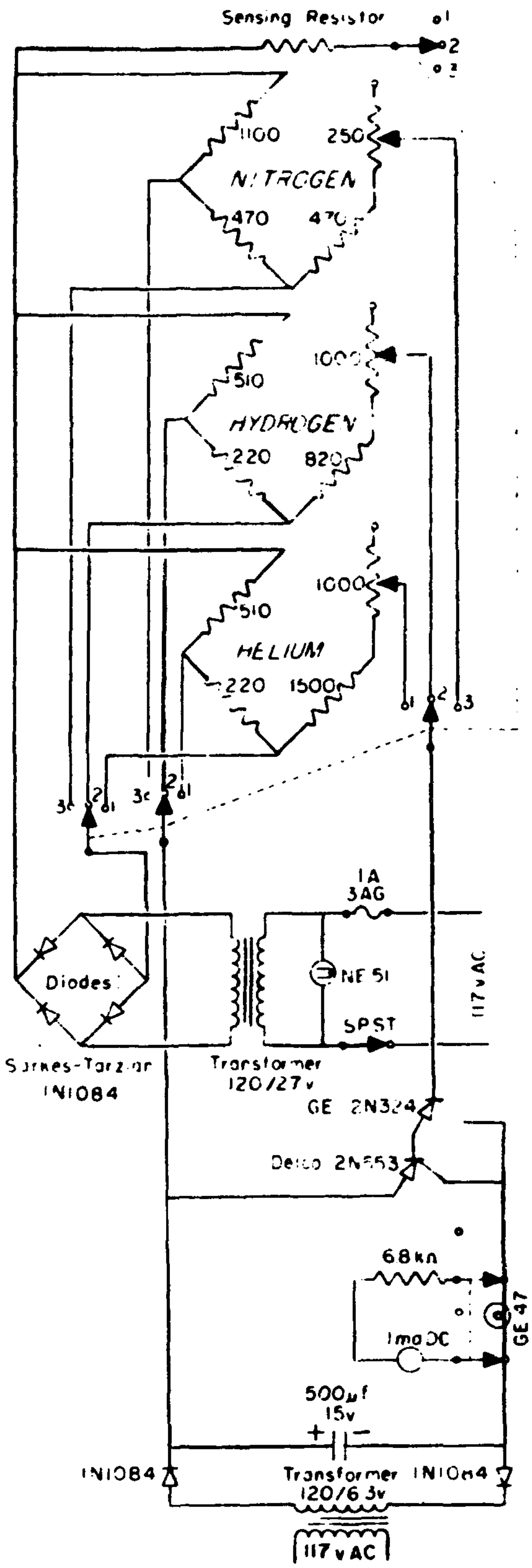


Figure 2

LIQUID LEVEL INDICATOR FOR LIQUID HELIUM, LIQUID HYDROGEN, AND LIQUID NITROGEN

be published shortly in "Review of Scientific Instruments". A copy of the paper will be included in a future report.

Flowmeter Survey

Due to the lack of flow test facilities at present, and no definite plans for any future facility, only a limited amount of test data is contained in the flowmeter survey. The survey compiled to date is based on manufacturers' literature, results of applications of meters in industry, a limited number of test reports, and several other surveys of flowmeters available from technical publications. Inquiries have been sent to most of the manufacturers of flowmeters applicable to cryogenic fluids; a few more will be sent out shortly. The inquiries have requested a physical description, operating principles and characteristics including range and accuracy, and price if commercially available. The first draft of the survey contains the information available at present and will be distributed shortly; continuous additions and revisions are being made as more information is received.

2.1 Forced Vibration Densitometer Studies

A test apparatus similar to the one shown in figure 12, First Quarterly Report, has been designed and built. Tests have been performed on the apparatus without fluid to establish the dynamic characteristics of the instrument. Results of these tests indicated several undesirable characteristics to be present. The most critical of these were frequent failures of the brass bellows due to over-stressing and work hardening, and harmonics which cause distortion in the dynamometer output signal.

The following modifications were made in an attempt to correct these:

a. The brass bellows were replaced by bellows of beryllium-copper.

b. The amplitude of the oscillating passage was decreased from 0.22" to 0.12".

c. Improved passage guides were designed and installed to insure only one degree of freedom for the passage.

A Statham dynamometer was selected to measure the force transmitted to the passage. This gage has a flat frequency response up to 3000 cps, a stiffness of 6×10^4 #/in. and a load capacity of ±10 lbs. It is assumed that with this stiffness the driver and passage motion may be considered in phase. A proximity pickup was installed to check the validity of this assumption. Calibration tests will be run as soon as the instrument proves to have suitable endurance and undesirable harmonics have been eliminated.

3. Cryogenic Design Principles and Materials Utilization

D. B. Chelton, L. E. Scott, J. A. Brennan and B. W. Birmingham

General assistance on Project Centaur has continued during the reporting period. Emphasis, however, has been placed on the design of low temperature observation windows for various containers, the preparation for testing of bearings for the zero-gravity centrifugal vent device and the adaptation of NBS developed seals for fuel line flange application.

A detailed discussion of some of the technical problems that have been considered on Project Centaur are described below. In addition to those described, discussions have been held with CVA personnel on other matters of general cryogenic importance such as properties of materials, temperature stratification, and instrumentation. Three visits to Convair Astronautics (CVA) were made by NBS

personnel. Several telephone conversations to assist CVA personnel have taken place. Also, CVA has visited NBS for assistance and to observe certain tests.

3.1 Observation Windows

Early in this reporting period, a CVA window frame for the Zero-G test container was brought to Boulder for both installing of the glass using epoxy adhesive and for low temperature testing. This window failed during cooldown. The frame design did not adequately limit the heat transfer from the outer window to the liquid hydrogen heat sink. Consequently, severe frosting of the window occurred. As a result, CVA designed a new window configuration which was reviewed by NBS. The redesign also had several problem areas, in particular, inadequate fin area and possible weak structure. Detailed comments on this new design were submitted in a letter report to CVA.

Assistance to several other CVA departments on window design for low temperature applications has also been given during visits. The discussions with CVA personnel on this general subject have indicated a need for a compilation of some of the design parameters necessary for a successful window. An informal report, NBS Laboratory Note 61-2, "Preliminary Notes on Cryogenic Windows" has been prepared to partially fulfill this need. A window to demonstrate the design parameters has been constructed in Boulder. The dimensions are similar to those required for the Zero-G test vessel. This window will be tested in the near future. An additional window, using the compressed O-ring seal principle reported elsewhere in this report, is also being investigated. A test apparatus, to determine the ability of the window to withstand the high loading forces required, is completed. Results of the tests will be available shortly.

Although considerable discussion has taken place with the various groups at CVA concerned with window designs, a number of designs have recently been seen in the CVA shop that CEL feels will fail.

3.2 Bearings for Zero-Gravity Vent Device

The possibility of using ball bearings in a centrifugal vent device was indicated in the First Quarterly Report. As was indicated in that report, bearings have been operated successfully in a cold gaseous nitrogen atmosphere under essentially no load. It is necessary to extend the testing to include tests under conditions similar to what is expected in the vent device.

To evaluate bearings operating in a hydrogen atmosphere, it was necessary to relocate the NBS test apparatus and make some modifications to the existing equipment. The tester has been moved and the modifications are nearing completion. Preliminary testing should start before February 1.

Actual testing will be concerned with finding a bearing that will operate reliably under conditions similar to what are expected in the venting device. The tests will be performed with the bearings running in a gaseous hydrogen atmosphere. The hydrogen gas will be cooled in liquid nitrogen before being introduced into the tester. During the tests the following information will be monitored: speed, load, torque and outer ring temperature of the test bearings.

The bearing test speed will be approximately 10,000 rpm, the anticipated operating speed of the vent device. Both radial and thrust loads will be encountered. However, only thrust loads can be applied to bearings tested in the existing apparatus. A thrust load equivalent to the combined radial and thrust loads that are expected will be placed on the bearings. Since the radial load is quite small compared to the

thrust load, this should not introduce inconsistencies between test results and their application. Torque will be measured as a function of time with a variable capacitor torquemeter. Temperature will also be measured as a function of time and coolant gas flow rate by attaching thermocouples on the outer rings of the bearings.

Possibilities other than unlubricated ball bearings appear feasible for the centrifugal vent device. Plans are presently being made to extend the bearing tests to include tests on sleeve type journal bearings, in particular bearings made of carbon compounds. Preliminary tests will be conducted submerged in liquid nitrogen. If successful bearings are established under these conditions, the tests will extend to operation in a cold gaseous hydrogen atmosphere.

3.3 Fuel Line Flange Seal

The fuel line flange currently used on the Centaur employs a pressure actuated "Teflon" jacketed metal seal. This seal has failed to perform properly in this application. Recent work* performed by NBS reports a technique which has made excellent seals under similar conditions.

Accordingly, an investigation to study the use of this seal in the Centaur application has been undertaken. Two test flanges (similar to the Centaur flange) were constructed as illustrated in figure 3. A test container was also constructed to allow the assembled flange to be pressure tested at liquid nitrogen temperature (-320°F). The flange was assembled as shown in figure 4 and placed inside the test container. The volume around the assembly was evacuated and connected to a mass spectrometer helium leak detector. The volume inside the flange

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*Weitzel, D. H., et al, "Elastomers for Static Seals at Cryogenic Temperatures", Paper D-6, Proceedings of the 1960 Cryogenic Engineering Conf., Boulder, Colorado, August 21-23, 1960.

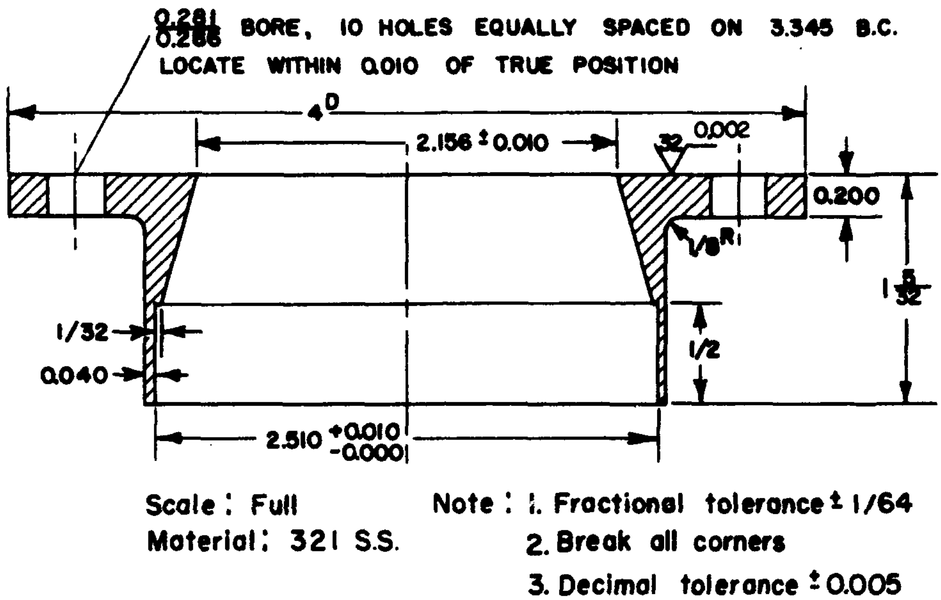

Figure 3

CENTAUR FUEL LINE FLANGE

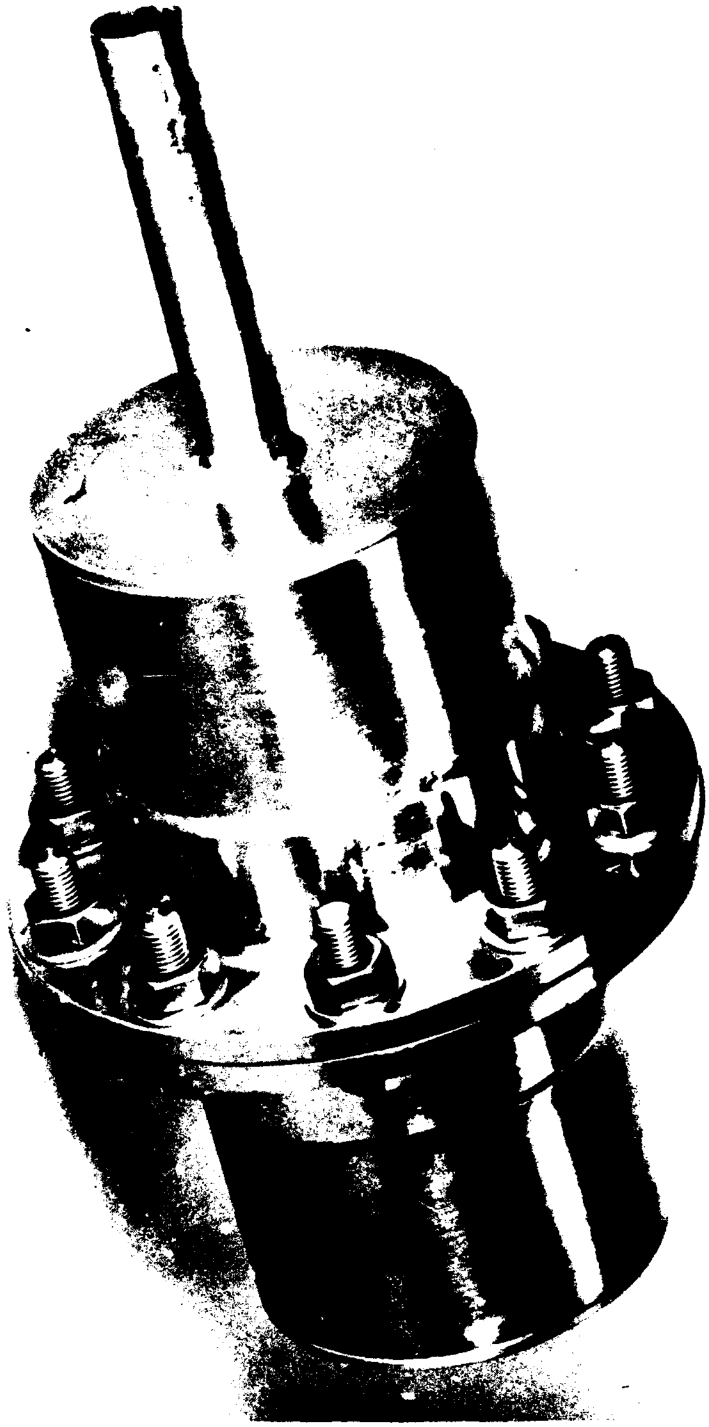

Figure 4

FLANGE ASSEMBLY

assembly could then be cooled to liquid nitrogen temperature and pressurized with helium gas. Any seal leakage would immediately be shown by the leak detector. The assembly was proof-tested to 225 psi and leak checked at 165 psi.

Three tests have, thus far, been performed with this apparatus. The first of these employed a neoprene O-ring, I.D. = 2.614 in., width = 0.070 in., obtained from Plastic and Rubber Products, Inc. (Parco), Los Angeles, California. The neoprene was designated as compound 307-50. The seal was made by installing the O-ring, as received from the manufacturer, between the two clean (degreased with trichloroethylene) flange faces. The unit was assembled by evenly tightening ten 1/4 inch N.F. cap screws to a torque of 120 in.-lb. When pressure tested, the seal was found to be leak tight on the most sensitive scale of the mass spectrometer at both room temperature and liquid nitrogen temperature. The seal assembly was temperature cycled from ambient to liquid nitrogen temperature three times, and pressure tested after each cycle. No leaks were indicated at any time.

Identical tests were made with two additional O-rings:

1. Parco Compound 921-65 ("Hypalon"), I.D. = 2.614 in., width = 0.070 in. Bolt torque = 70 in.-lb.
2. Neoprene, O.D. = 2-3/4 in., width = 0.139 in. This standard O-ring was a rather hard compound carried in NBS-CEL stock for general high-vacuum use. Bolt torque = 120 in.-lb.

Both of these tests were as promising as the first, with no leaks indicated.

It is interesting to note that the flange edges, on tests one and two, were touching at the bolt torque indicated.

The susceptibility of these seals to vibrational loads was not explored in these preliminary tests. Previous confined seals in similar applications have demonstrated ability to withstand vibration.

These seals appear promising for the Centaur application. The present testing was done at liquid nitrogen temperatures only. Past experience with these materials, however, indicates that service at liquid hydrogen temperature would have no further detrimental effects, which were not already apparent at liquid nitrogen temperature.

The encouraging results warrant further investigation of the possible application to the fuel line flanges. The preliminary results have been given to CVA and a joint program established. NBS will perform additional thermal and pressure tests on the above sealing method and on other more conventional commercial seals. CVA will perform vibration tests on the successful seals. Physical retainment of the seals for field installation will be considered by NBS and CVA.

3.4 Ground Support Equipment

Several general discussions were held with CVA personnel concerning ground support equipment. These had particular application to facilities at Point Loma and Sycamore Test Sites. The subjects of transfer lines, storage tanks, high vacuum insulation and powder-vacuum insulation were considered.

A contamination problem has been encountered involving the pressurizing gas used for fuel transfer. The helium gas used for this purpose contains several hundred parts per million of oxygen and nitrogen in the proportions of air. The potential hazards of the accumulated air and methods of avoiding the initial contamination were discussed. Based on past experience and experimental programs concerned with the potential hazards of solid air in liquid hydrogen, it was concluded that although no particular hazard existed, steps should be taken to prevent the initial contamination of the helium.

3.5 Propellant Tank Insulation

Insulation for the propellant tank has application to the Propellant Test Vehicle (PTV) and the Centaur Vehicle. The PTV insulation is quite heavy compared to the Centaur Vehicle in order to simulate the heat transfer encountered in space. It is of immediate concern to obtain a successful insulation for such application. The Centaur insulation is divided into that which is jetisoned during flight and that which remains aboard on the fuel tank forward bulkhead. Success of the insulation is of utmost importance.

During the reporting period, sprayed on foam was applied to two PTV tanks. The PTV located at Sycamore has been cooled on several occasions. On the first cooldown the insulation exhibited typical failures -- circumferential cracks, radial cracks and poor adhesion. On subsequent cooldowns, the initial failures propagated. The effectiveness of the insulation is quite poor.

Although no immediate solution to the problem is apparent, it is felt that further study should not be de-emphasized. Suggestions on a possible program of research and development have been prepared. Further study should include not only attempts to obtain an immediate solution, but also a long-range development program.

4. A Compilation of Thermophysical Properties of Cryogenic Materials

R. B. Stewart and V. J. Johnson

The task of compiling data of cryogenic materials was started at CEL in January 1958. This early effort culminated with the publication of the preliminary report, "A Compendium of the Properties of Materials at Low Temperature", Phase I, in December 1959. The scope of this activity was later increased in January 1959 to include

seven additional properties which was the beginning of the work now being carried on in this project.

Extensive bibliographies have been prepared for this second phase of this activity on the following subjects:

1. Compressibility Factor of Cryogenic Fluids.
2. Compressibility and Compressibility Coefficients of Cryogenic Fluids.
3. Entropy Data for Cryogenic Fluids.
4. Velocity of Sound for Cryogenic Fluids.
5. Solubility of 2-Component Mixtures of Cryogenic Fluids.
6. Electrical Resistivity (and Conductivity) of Materials at Low Temperatures.
7. Ferromagnetic Properties of Materials at Low Temperatures.

(The cryogenic fluids of primary interest are: Helium, Hydrogen, Neon, Nitrogen, Oxygen, Air, Carbon Monoxide, Fluorine, Argon and Methane.)

A task of assembling thermal conductivity integrals of cryogenic materials was completed from work done in Phase I. (The thermal conductivity integral is a cumulative value of thermal conductivity from the datum temperature rather than an instantaneous value.) This material is compiled in tables for 44 pure metallic substances, 36 non-ferrous alloys, 9 ferrous alloys and 4 glasses and plastics.

The compilation and correlation of data and the presentation of the results on completely documented data sheets in the current established program is progressing. These data sheets usually contain graphical presentation of the data in a form that is particularly useful for engineering information. In addition, the data sheet includes a documentation of the data sources, information on methods of analysis of the data and basis for selection of the data used together with comparisons of alternate sources when available. Tables of selected values are also included.

Data sheets are currently being prepared for the subjects included in the above bibliographies. These data sheets are in various stages of completion for the materials currently being considered. Many of the data sheets, in particular on compressibility factor, velocity of sound, solubility and electrical resistivity are in the final stages of review for issuance.

The following is an indication of the current status of tasks worked on during the reporting period, together with an estimate of their completeness:

1. Compressibility Factor for Cryogenic Fluids ($Z = PV/RT$) (data sheets for hydrogen, nitrogen, methane and air were completed previously)

   Argon (1 to 5000 atm., 120 to 300°K)(70% completed)
   Helium (1 to 100 atm., 20 to 300°K)(50% completed)
   Neon (20 to 90 atm., 55 to 300°K)(100% completed)

2. Entropy for Cryogenic Fluids (T-S diagram with constant property lines for pressure, volume, enthalpy)

   Neon (20 to 90 atm., 55 to 300°K)(60% completed)
   Helium (1 to 100 atm., 20 to 300°K)(30% completed)
   Nitrogen (1 to 3000 atm., 90 to 300°K)(20% completed)

3. Solubility and Phase Equilibria of 2-Component Mixtures (solid, liquid, gas phases). About 28 data sheets are in various states of preparation. (This task is now about 80% completed.)

4. Electrical Resistivity of the Pure Metals. Data sheets for 21 metals have been completed for review. Data sheets for 25 metals are in progress and are about 80% completed.

In addition to continuing the tasks now in progress to the completion of several data sheets in the next reporting period, it is anticipated that active preparation of data sheets will be undertaken for the subjects for which bibliographies are now available. Additional materials and an increased number of fluids will also be considered, providing adequate staffing can be made available.

U.S. DEPARTMENT OF COMMERCE
Frederick H. Mueller, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colo., is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

ELECTRICITY. **Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics.**

METROLOGY. **Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Scale. Volumetry and Densimetry.**

HEAT. **Temperature Physics. Heat Measurements. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research. Equation of State. Statistical Physics. Molecular Spectroscopy.**

RADIATION PHYSICS. **X-Ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.**

CHEMISTRY. **Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.**

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ORGANIC AND FIBROUS MATERIALS. **Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.**

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Office of Weights and Measures.

BOULDER, COLO.

CRYOGENIC ENGINEERING. **Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.**

IONOSPHERE RESEARCH AND PROPAGATION. **Low Frequency and Very Low Frequency Research. Ionosphere Research. Prediction Services. Sun-Earth Relationships. Field Engineering. Radio Warning Services.**

RADIO PROPAGATION ENGINEERING. **Data Reduction Instrumentation. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation-Terrain Effects. Radio-Meteorology. Lower Atmosphere Physics.**

RADIO STANDARDS. **High frequency Electrical Standards. Radio Broadcast Service. Radio and Microwave Materials. Atomic Frequency and Time Standards. Electronic Calibration Center. Millimeter-Wave Research. Microwave Circuit Standards.**

RADIO SYSTEMS. **High Frequency and Very High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Space Telecommunications.**

UPPER ATMOSPHERE AND SPACE PHYSICS. **Upper Atmosphere and Plasma Physics. Ionosphere and Exosphere Scatter. Airglow and Aurora. Ionospheric Radio Astronomy.**